VOLUME XXXIII NUMBER 5

THE
JOURNAL OF GEOLOGY

July-August 1925

THE VERMILION BATHOLITH OF MINNESOTA[1]

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ABSTRACT

This paper is a summary of the petrography and petrology of the largest granite batholith in Minnesota. The granite is of Algomian age and reached its position partly by crowding out its walls and largely by stoping upward into mica schists. Its main phase is a fresh biotite granite of no great peculiarity. Its minor phases, modified by metamorphism or assimilation, are of little importance. A series of satellitic stocks are notably alkalic.

Along the edges of the granite there are considerable masses and an interrupted belt of darker, usually hornblendic rock. In places this has differentiated into banded rocks of considerable variety, syenites, shonkinites, pyroxenites, and even magnetite rock. This series is not common in granite batholiths. It probably indicates the general course of evolution in the pre-Cambrian batholiths of the Canadian shield, few of which have been studied in detail. Several new analyses of special phases are given, and it is suggested that they separated by crystallization during convection. A convection circulation past the cooling walls of a batholith might account for the almost vertical position of the banded differentiates.

INTRODUCTION

Undoubtedly the largest granite batholith of northern Minnesota is that north of Vermilion Lake, here called the Vermilion granite. Its bounding formations are so altered and injected that it has been a difficult problem to map it for a report;[2] and its age relations in

[1] Published by permission of the director of the Minnesota Geological Survey.

[2] A bulletin on the geology and magnetite deposits of northern St. Louis County is nearly ready for the press. The mass has been shown, in part, in maps of the *Final Report of the Minnesota Geological and Natural History Survey*, Vol. IV; and the parts in Canada were mapped by W. H. C. Smith, "Geology of Hunters Island," *Canada Geological Survey Annual Report*, Vol. V G, 1892.

such metamorphosed surroundings have been determined only with considerable difficulty. This has involved much petrographic work, which is here compiled.

GENERAL GEOLOGY

Occurrence and field relations.—The batholith occupies the northern part of St. Louis County, Minnesota. Schistose pre-Cambrian formations lie north and south of it. Westward the contacts are largely concealed under the drift, but the granite probably extends only a short distance; for mica schist is exposed at many points along the Little Fork River, where granite would be expected to form even larger exposures if it were present. On the east and southeast the biotite granite has first a related hornblende syenite and then gneisses and schists of greater age (Fig. 1). The syenites and basic differentiates make up about 5 per cent of the area. The gneisses referred to as older are distinguished not only by their greater metamorphism, but by differences in composition. A narrow belt of such gneiss occurs near Burntside Lake, and a larger mass on Brent Lake in Canada. It is possible that south of Brent Lake the Vermilion batholith is really continuous with other granite masses in Canada,[1] but if so the connection is restricted to a belt not over 10 miles wide, half of which is a hornblendic border phase. The granite may also be more remotely connected underground with the granites of Rainy Lake, of Hunters Island, and of the Giants Range. A mass on Long Lake north of Hunters Island and some masses on Rainy Lake seem petrographically identical with the Vermilion granite, and have hornblendic border phases strikingly like those described in this paper.

The outcrops over an area 30 by 80 miles are numerous, but many of them show special phases. The main typical fresh granite is exposed southeast of Namekan Lake, on Lac la Croix, and some adjacent areas in a broad zone nearly 10 miles wide, with hardly even a pegmatite to break its uniformity. Elsewhere the granite is mostly filled with inclusions and crossed by pegmatites and aplites; in short, all the modifications characteristic of the upper portions of batholiths. About nine-tenths of the inclusions are mica schist of

[1] As suggested by Smith, *op. cit.*, pp. 18–19.

sedimentary origin, but there are some amphibole rocks and various others.[1]

Contacts and contact action.—Much of the edge of the batholith is so complicated by dikes and *lit-par-lit* injection that no line can be

FIG. 1.—Sketch map showing the general geologic setting of the Vermilion batholith and its satellites, and special phases.

drawn as a satisfactory limit. The granite intrudes all the older rocks of the region, but only dikes have been seen in contact with the Soudan formation. Other formations are variously affected. Further studies of contact action are in progress.[2]

[1] The abundance of concordantly injected mica schist might in places make the term "stromatolith" applicable. See *Journal of Geology*, Vol. XXIV (1916), p. 791.

[2] One is already published by G. M. Schwartz, "Effect of Granite and Gabbro Intrusions on the Ely Greenstone," *Journal of Geology*, Vol. XXXII (1924), pp. 89–138.

Mode of intrusion.—Many investigators agree that batholiths reach their places by two distinguishable modes of intrusion.[1] In great depths, the roof and walls may be crowded aside, moving by rock flowage as the magma rises. In the zone of fracture, the roof and walls have a chance to yield by stoping and slight doming up at the surface.

The Vermilion batholith shows abundant *lit-par-lit* injections of its walls, and the strike of the structure in the walls is roughly parallel to the contact. These facts suggest a crowding action at considerable depth. There is also, however, such a remarkable abundance of schist inclusions in much of the granite area that it is evident that the magma was working its way upward by stoping. Probably it had reached a moderate depth and both processes here acted at the same time.

One feature may be considered as a limit to the amount of stoping accomplished. A relatively basic hornblendic rock on the borders of the batholith seems to be a relic of an early stage of the magma. It is largely syenite, but has in places even more basic phases. If, as it seems, this rock solidified from the magma early, the stoping done during the long process of differentiation to granitic composition was not sufficient to remove all the early basic separates. Probably during the differentiation little stoping was done except to form the inclusions now indicated by the outcrops.

Age.—The mica schists, so clearly intruded by the granite both on the north and south, are equivalent to the Knife Lake slates, Lower-Middle Huronian.[2]

The other limit to the age of the granite is less accurately determined. No sediments later than the Knife Lake slates have been found in contact with the granite, except the drift. The granite is without doubt as old as early Keweenawan, for fresh basalt and diabase dikes cut across it in several places.[3] Such dikes in Minne-

[1] Sidney Paige, "Intrusion of Black Hills Granite," *Geological Society of America Bulletin*, Vol. XXVII (1916), pp. 104–5, and discussion by Joseph Barrell.

[2] Frank F. Grout, "The Coutchiching Problem," *Geological Society of America, Bulletin*, Vol. XXXVI (1925). In press.

[3] Sec. 23, T. 63 N., R. 18 W. Specimens 2,000 to 2,004 of the Survey are from basalt dikes. See *Twenty-fourth Annual Report*, pp. 7–9. See also *Final Report*, Vol. IV, pp. 539–40, 243. A basalt dike cuts across pegmatite in the channel from Sand Point to Namekan lakes.

sota are not known to be later than Keweenawan. Whether it is early Keweenawan[1] or Algomian is not easily settled; but the petrographic series resembling, even in minute detail,[2] that of the Algomian granite of the Giants Range and that of the Kekequabic and Snowbank stocks, which are supposed to be Algomian, indicates that the Vermilion mass is also Algomian.[3]

Name.—The name Vermilion is applied to this granite from the abundant exposures along the Vermilion River, flowing north practically across the center of the batholith. Exposures are also clear along the north shore of Vermilion Lake, which is the source of the river. The name Vermilion was once used by the Minnesota Survey for a formation, group, or series of metamorphic rocks in this district; but as first used it was soon found to consist of several formations where altered by granite intrusives.[4] The name was therefore dropped.

PETROGRAPHY OF THE MAIN MASS[5]

The Vermilion granite of most outcrops is a normal granite of no peculiarity. The texture is uniformly equigranular over large areas. Locally in two small patches the rock has feldspar phenocrysts up to an inch in length. Finer-grained prophyries have been seen only in the smaller satellitic masses.

The mineral composition of the granite varies but little from the following: quartz 25 per cent, orthoclase[6] 30 per cent, microcline[6]

[1] To be correlated with Killarnean; see T. T. Quirke, "Correlation of Huronian and Grenville Rocks," *Journal of Geology*, Vol. XXXII (1924), p. 332.

[2] Frank F. Grout, "A Peculiar Shonkinite Related to Granite," *American Journal of Science*, 5th Series, Vol. IX (1925), pp. 472–80.

[3] Spelled in accordance with nomenclature of other periods. This assignment of the greatest of Minnesota granites to Algomian leaves very little Laurentian, as commonly understood. A small dike of granite gneiss on Rainy Lake and the Saganaga granite (largely in Canada) are the only clear cases, in the state, of granite old enough to supply pebbles to the Lower-Middle Huronian conglomerates.

[4] See *Fifteenth Annual Report, Minnesota Geological and Natural History Survey*, et seq.

[5] The petrographic notes of the Minnesota Geological and Natural History Survey on this granite are mostly in the *Final Report*, Volume V, scattered under some forty numbers which can hardly be distinguished from others. Few samples were taken except on Vermilion and Burntside lakes. Some field work by Alexander Winchell in 1887 was reported in the *Sixteenth Annual Report*, pp. 332–33.

[6] The analyses and indices of refraction indicate some soda in the potash feldspars.

20 per cent, oligoclase 20 per cent, biotite 2 per cent, accessory apatite, zircon, and allanite; with traces of magnetite and muscovite in a few places. See Figure 4. Epidote, chlorite, and kaolinite are common secondary products in small amounts. Biotite as the essential mineral of variable composition was separated, purified, and tested. See Table I. Its specific gravity is 3.107; gamma = 1.640 ± 2; alpha = 1.597 ± 5. It has a medium-brown color.

TABLE I

PARTIAL ANALYSIS OF BIOTITE FROM VERMILLION GRANITE

SiO_2	37.12	Na_2O	.68
Al_2O_3	17.06	K_2O	5.40
Fe_2O_3	4.05	H_2O+	3.10
FeO	14.80	H_2O-	.30
MgO	10.21	TiO_2	2.23
CaO	2.36	MnO	.48
			97.79

The chemical composition of the granite is shown by analyses 1 and 2 of Table VI. Table II shows the approximate uniformity of the material from widely separated outcrops.

TABLE II

PARTIAL ANALYSES OF NORMAL VERMILLION GRANITE

	1	2	3	4	5	6	7
Fe_2O_3	.58	.46	2.25	.93	1.31	.....	1.67
FeO	1.35	.72					
Na_2O	3.58	4.56	3.90	3.73	3.77	3.01	3.79
K_2O	4.63	3.54	4.72	5.36	5.06	5.70	4.83
Specific gravity	2.615	2.637	.....	2.611	2.618	.....	2.644

1. From the northwest part of Sand Point Lake, Sec. 12, T. 68 N., R. 17 W.
2. From southeast of Pelican Lake, T. 64 N., R. 19 W.
3. From Sec. 23, T. 65 N., R. 15 W.
4. From Sec. 10, T. 66 N., R. 17 W., near the chief prospect hole in magnetite pegmatite.
5. From Sec. 24, T. 66 N., R. 18 W.
6. From Sec. 10, T. 66 N., R. 15 W.
7. From Sec. 21, T. 66 N., R. 13 W.

GNEISSIC BORDER PHASE

On the shores of Namekan Lake, from Sec. 18, T. 69 N., R. 18 W., east nearly to Sand Point Lake the granite is gneissic. The ex-

posures near shore might lead one to suppose the gneiss was a distinct formation. In the bay, in Section 36, however, there are within a mile all gradations from gneissic to massive granite. The connection of this gneiss with the Algomian granite is also indicated by its composition. It contains 2.76 per cent soda and 5.37 per cent potash, closely resembling the granite of which analyses are given in Table II.

Microscopically the gneisses show only a slight granulation and scarcely any augen structure. See Figure 5. None of the minerals of the granite is wholly obliterated, but the biotite has largely altered to muscovite, and both micas are commonly bent. There is rather more of graphic and perthitic intergrowth than in the average granite.

EARLY BORDER PHASES

On Basswood Lake along the international boundary there is a considerable area of hornblende syenite. It is not only trachitoid in its primary state, but more metamorphosed than the biotite granite of the Vermilion batholith, and it is intruded by that granite, especially by its aplites and pegmatites. For a time it was considered a distinct intrusive earlier than the Vermilion granite, but several features indicate that the two are closely connected. In the first place, the rock occurs not only in a wide area at Basswood Lake, but in a narrow elongated belt following the border of the granite, more or less intermittently, for many miles. See Figure 1. It intrudes the Knife Lake slates just as the granite does.[1] The neighboring intrusives of Rainy Lake, Pooh Bah Lake, Snowbank Lake, Kekequabic Lake, and that of the Giants Range each has a series of differentiates through syenite to some dark rock; and shonkinites (Basswood type) are found in three of them in the same relation to granite as here in the Vermilion.[2] Finally, when the whole area was studied, it was found that many outcrops between the Basswood and Vermilion areas are of intermediate rocks. While there is evidently a sequence in the solidification of the rocks, dark syenite being in-

[1] The statement in *U.S. Geological Survey Monograph 45*, p. 261, that the rock at Basswood Lake is pre-Huronian seems to be an error. It may be seen intruding Ogishke conglomerate.

[2] Frank F. Grout, *op. cit.*

truded by light syenite and both intruded by granite, a series of intermediate rocks can be selected showing scarcely a break from granite to hornblendite. No single outcrop shows a good gradation,

FIG. 2.—Syenite on the shore of Basswood Lake, weathering into slabs

FIG. 3.—Banded syenite southwest of Basswood Lake; spotted shonkinite (Basswood type) here alternates with light syenite.

but in a broad way the relation of the several rocks to a single period of batholithic injection can hardly be doubted.[1]

The main rock near Basswood Lake is a gray trachitoid syenite which weathers with a pronounced tendency to form slabs a few inches thick (Fig. 2).[2] Its mineral composition is approximately 40 per cent oligoclase, 20 per cent orthoclase, 30 per cent hornblende, 5 per cent quartz, and 3 per cent biotite, with accessory magnetite, apatite, and titanite. See Figure 6. Its composition is shown by analysis 8, Table VI.

On Basswood Lake, as well as elsewhere, the border rock has many bunchy segregations and much of the rock is banded (Fig. 3). The bands are nearly vertical and strike roughly parallel to the boundary of the batholith. A quartzose phase, hornblende granite gneiss, occurs at Prairie Portage on the east side of the mass, and from there southwest many miles; while similar rocks are known at the north edge on Coleman Island, and reported from the west side.[3] Locally in patches and bands the syenite grades into phases that are notably biotitic, or hornblendic, or magnetitic. One small band was found to have andesine feldspar, and should probably be classed as diorite.

The peculiar spotted shonkinite (Basswood type)[4] is seen at many places near the border of the granite. The amount of hornblende in this type is variable but characteristically above 50 per cent. Much of it forms bands a few inches to a few feet wide alternating with syenite and hornblendite. Its composition is probably very close to that of a rock from the Giants Range, analyzed by Dr. Allison—about 50 per cent silica, 9 per cent alumina, and 4 per cent alkalies.

A banded magnetite segregation has been found in the same

[1] Some dark phases near a greenstone contact might be supposed to be hybrid or contact rocks, especially since poikilitic textures are present as they commonly are in contact rocks. The dark rocks here described, however, are found not only near dark walls, but in some places adjacent to an older granite gneiss.

[2] Noted by A. Winchell as early as 1887: *Minnesota Geological and Natural History Survey, Sixteenth Annual Report*, p. 332.

[3] N. H. Winchell, *Minnesota Geological and Natural History Survey, Final Report*, Vol. V, No. 931, 1900.

[4] Grout, *op. cit.*

series of differentiates grading from syenite to hornblendite.[1]

The hornblendite in this border rock is almost indistinguishable in hand specimens from the metamorphosed Ely greenstone near by; but the occurrence in a series of bands clearly proves it to be a differentiate from the batholithic magma. It has about 80 per cent green hornblende, and 5 per cent biotite, with a little feldspar, magnetite, and apatite (Fig. 7). The hornblende, like that in the main syenite, has an index gamma = 1.667 ± 5, evidently a not unusual variety.[2]

TABLE III

THE CONTRASTING COMPOSITIONS OF VERMILION GRANITE AND ITS BORDER PHASES

	Normal Granite Average	Syenite Basswood Lake, No. 8	Syenites and Shonkinites of Vermilion Lake				Diorite, Small Band, No. 18	Hornblendite, High Lake, No. 13	Ore, High Lake, No. 14
			No. 9	No 10	No. 11	No. 12			
Silica	71.90	57.12	58.55	.....	.....	.....	.....	38.13	5.69
Iron as Fe_2O_3	1.58	7.07	7.33	11.40	.....	.....	.....	21.83	77.89
Magnesia	.80	4.60	8.63	.....	.....	.....	.....	11.55	3.70
Potash	4.06	1.36	2.01	3.49	2.21	2.87	1.53	.43	.24

The biotite in thin section has a pale-brown color and an index gamma = 1.633 ± 5, probably low in iron for a mineral in such a ferruginous rock.[3] An analysis of the hornblendite is No. 13 of Table VI.

The variety in mineral composition of these bands in the border phases of the Vermilion batholith is shown in Figure 10, the diagram of a few measurements. All intermediate compositions could easily be collected. The contrast in chemical compositions is shown very clearly by a few determinations of alkali content (Table III).

ASSIMILATION PHASES

Two of the rocks intruded by the Vermilion granite differ from it so notably that included fragments are very conspicuous. Frag-

[1] Frank F. Grout, "A Magnetite Segregation in Banded Syenite in Minnesota," *Economic Geology*, Vol. XX (1925). In press.

[2] A. N. Winchell, "Studies in the Amphibole Group," *American Journal of Science*, 5th Series, Vol. VII (1924), pp. 287–309.

[3] Frank F. Grout, "Notes on Biotite," *American Mineralogist*, Vol. IX (1924), p. 159.

FIG. 4.—Typical Vermilion granite; dusty areas orthoclase; a small amount of biotite. ×14.

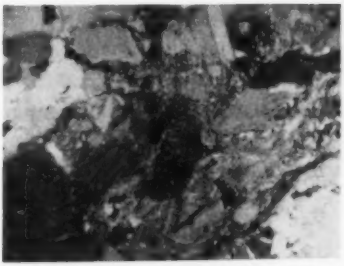

FIG. 5.—Gneissic Vermilion granite from Namekan Lake; bent biotite and broken feldspars. ×28.

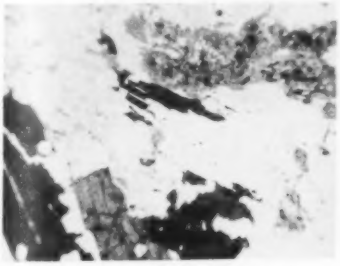

FIG. 6.—Syenite from west of Basswood Lake; abundant hornblende and little biotite. ×14.

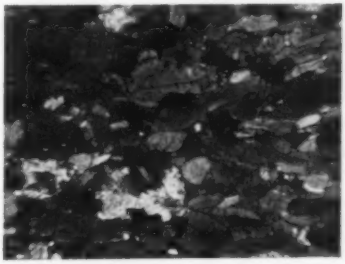

FIG. 7.—Hornblendite, west of Basswood Lake. ×14.

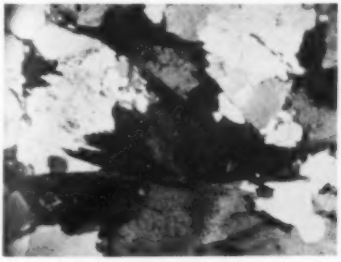

FIG. 8.—Vermilion granite with much biotite, apparently assimilated. ×28.

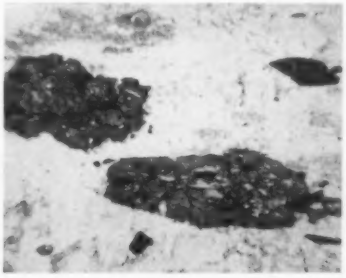

FIG. 9.—Linden syenite; wedges of titanite and large grains of green pyroxene in a matrix of elongated feldspars. ×14.

ments of the Knife Lake slate form dark biotite schist, and those of the Ely greenstone form dark hornblende schist, when included in light pink granite. The two rocks, however, reacted differently with the granite magma.

In a few small areas hornblendite inclusions possibly derived from Ely greenstone are abundant. The hornblendite is evidently pervasively soaked in granite juices. The altered part of the inclusion shows a progressive change from hornblende granite gneiss to biotite granite gneiss,[1] and outside the inclusion there are a few biotitic schlieren. These schlieren probably indicate about the extent of real assimilation. The biotite granite has not been found to become hornblendic near the hornblendic inclusions anywhere in the batholith.

Most of the granite area is characterized by an abundance of biotite schist inclusions, but there is little sign of solution of the fragments. The schist has 10 to 20 per cent of biotite, and most of the granite only 2 or 3 per cent; but in a few places the granite near the inclusions is slightly darker than average. Compare Figures 4 and 8. Such rocks are exposed on Gun Lake and Murphy Lake in the eastern part of the area mapped. These are quite apart from those mixed rocks that show traces of schist structures, and they cannot be considered extreme phases of injected schist; they are granite. Several features combine to indicate, however, that the granite has been affected by the digestion of some schist. The fragments of schist are rounded at the corners, and the cleavage plates on the sides are injected *lit-par-lit* until they float off into the granite as schlieren more and more indistinct. Finally, not only biotite but other constituents show that the darkened granite is intermediate between normal granite and biotite schist. It may be noted that a 20 per cent addition of schist would produce this much modification of the granite, and since the dark granite is not common, assimilation was probably not of great importance at that stage of magma history. See Table IV. The complete analysis of the modified granite is No. 15 in Table VI.

[1] G. M. Schwartz, *op. cit.*

PEGMATITIC PHASES AND IRON ORE

Pegmatites and aplites occur abundantly through most of the area of the batholith and in the schist walls and inclusions. North of the granite a number of large dikes follow approximately the structure of the schist and form great ridges, 40 to 50 feet wide. These have been noted for their coarse muscovite, but the quality of this mineral is not promising. Much more abundant but usually smaller masses of pegmatite occur within the area mapped as granite. In several cases a pink pegmatite crosses a white pegmatite as if distinctly later. These later pegmatites have locally some accumulations of coarse magnetite which aroused the interest of prospectors, and they have been given detailed study.[1] Note has been made also of some ladder veins crossing the pegmatite.[2]

TABLE IV

PARTS OF ANALYSES SUGGESTING ASSIMILATION

	Vermilion Granite, No. 1	Biotite Schist near Vermilion Lake	Calculated Mixture 4 Parts No. 1 and 1 Part Schist	Supposed Assimilation Phase of Granite, No. 15
SiO_2	71.73	63.04	69.99	69.01
Al_2O_3	14.76	16.45	15.10	16.92
MgO	.62	5.04	1.50	1.28
CaO	1.18	3.17	1.58	2.67

The chief minerals of the pegmatite are pink microcline, or its graphic intergrowths with quartz, white to greenish albite (or oligoclase), and quartz. Biotite is the chief dark mineral, but there are locally magnetite, muscovite, garnet, and tourmaline, and commonly all dark minerals are absent. Pyrite and chalcopyrite cross the early minerals in some of the magnetite deposits. Quartz in the average pegmatite is probably less than 20 per cent. The extreme compositions noted are (1) those with almost 100 per cent quartz, (2) those nearly all acid feldspars, and (3) those with about 50 per cent magnetite.

[1] Frank F. Grout, "Magnetite Pegmatites of Northern Minnesota," *Economic Geology*, Vol. XVIII (1923), pp. 253–69.

[2] Frank F. Grout, "Occurrences of Ladder Veins in Minnesota," *ibid.*, pp. 494–505.

The texture of the pegmatites shows the usual variation, and aplites are associated in many places, occurring even in the same dike in rudely banded structures. Banded pegmatites are not common, however, though many dikes show a central zone more quartzose than the borders.

The chemical composition is naturally variable. Analysis No. 16 of Table VI is from a sample of the average magnetite rock at a prospect hole. No other analyses have been made, but it is clear from the minerals that the ratio of soda to potash is variable, and silica may rise to the practical exclusion of all other constituents.

DIKES AND SATELLITES

Igneous rocks of small surface outcrop, near the Vermilion granite, may be related to the granite. The pegmatites north of the main area have been mentioned above. South and east along Vermilion and Burntside lakes, the granite fades into the schists in a series of irregularly diminishing dikes and *lit-par-lit* injections, so that its boundary can hardly be mapped. Several masses of granite lie far out between the Vermilion and Giants Range areas, suggesting a possible relationship between the two batholiths. Some of the larger are petrographically like the biotitic Vermilion granite, others are hornblendic like the border rock on Basswood Lake.

Several dikes intrusive into the rocks of the Vermilion district are also closely similar in age and composition to Vermilion granite. Probably they should be considered as apophyses unless they can be shown to be older than the Huronian sediments of the district. Their textures range from granitoid to porphyritic, and in some of the porphyries, quartz is found only in the ground mass. Several such intrusives cut the ore bodies of the Vermilion range.

Many intrusives of composition more basic than the granite also cut the Huronian sediments. The dark dikes of fresh rock are considered Keweenawan, but the more altered rocks may well be apophyses from the border-phase magmas of the Vermilion batholith. Some show the peculiar and almost distinctive petrography of the border phase. Furthermore, the location of some dark dikes very near and south of the southern border phase on Burntside Lake shows that such dikes are to be expected in other places.

Two masses of alkaline syenite lying between the Vermilion and Giants Range granites have less certain connections. One lies along the southwest side of Vermilion Lake, and the other in Linden Grove Township at the west side of St. Louis County. See Figure 1. They are not noticeably altered, and the one on Vermilion Lake is intrusive into the Knife Lake slates. Possibly they may be as young as Keweenawan, but there is little petrographic similarity to the Keweenawan diabases or their differentiates. They are here tentatively correlated with the Vermilion granite, and this is made the more probable by a similar satellite north of the granite, at Pooh Bah Lake, Ontario; see Figure 1. With almost identical field relations to the same granite, the rock at Pooh Bah Lake is even more alkalic—a malignite, Lawson called it.[1] In some degree, also, the syenites of Snowbank and Kekequabic lakes may be considered similar satellites, and suggest the generalization that alkalic differentiates are widely characteristic of Algomian granites in Minnesota.

Both of these alkalic syenites southwest of the batholith are characterized by a trachitoid structure based on lathlike feldspars with interstitial dark minerals. This structure trends north of east. The rocks are a purplish pink, but certain phases weather nearly white.

The feldspar in the Linden syenite is a light-purplish microcline-microperthite, and makes up about 80 per cent of the rock. The dark mineral is a green pyroxene in subhedral grains slightly elongated in the same direction as the feldspars. See Figure 9. Quartz and titanite are usually present in smaller amounts.

The pyroxene, as the variable mineral of the rock, has been separated and tested. Its indices of refraction are: gamma = 1.740 $\pm$4, beta = 1.728$\pm$6, and alpha = 1.720$\pm$4. Its optic angle is large. It has altered in places to pale-brown biotite with low index of refraction,[2] and glaucophane. These characters have been seen in no other pyroxene in Minnesota, but resemble those of the augites of the porphyry at Kekequabic Lake, and of the malignite at Pooh

[1] A. C. Lawson, "On Malignite," *University of California Department of Geology Bulletin 1*, p. 343, 1896.

[2] Probably less than 15 per cent iron oxides in the biotite. See *American Mineralogist*, Vol. IX, p. 163.

Bah Lake, in Ontario. An analysis (A) of this pyroxene is given in Table V, beside that of the Kekequabic mineral (B). The material analyzed may have had as much as 5 per cent of impurities, mostly titanite and the products mentioned as derived by alteration of the pyroxene. Its specific gravity is 3.361.

The analysis (A) shows the pyroxene in the Linden syenite to be largely diopside with both acmite and hedenbergite in notable amounts. It contains soda enough to show the alkalic nature of the syenite as a whole.

The analysis of the Linden syenite is given as No. 17 of Table VI. Its high potash content, 6.32 per cent, is noteworthy. This is greater than the potash content of average glauconite deposits, and as great as some that have aroused interest as possible potash-producers. The syenite on Vermilion Lake is more sodic: 7.45 per cent soda, and 2.39 per cent potash. Analyses of the other alkaline syenites are given in the references cited.

TABLE V

ANALYSES OF PYROXENES FROM MINNESOTA SYENITES

	A*	B†		A	B
SiO_2	46.85	53.19	Na_2O	2.49	2.63
Al_2O_3	2.50	2.38	K_2O	.50	.38
Fe_2O_3	11.40	9.25	H_2O+	.92	.01
FeO	6.72	5.15	H_2O-	none	.....
MgO	8.17	9.43	TiO_2	2.13	n. d.
CaO	17.85	17.81	MnO	.31	n. d.
				99.84	100.23

* Analysis of pyroxene from the Linden syenite, by the writer.

† Analysis of green augite from porphyry at Kekequabic Lake, by Dr. U. S. Grant. *Minnesota Geological and Natural History Survey, Twenty-first Annual Report*, p. 48, 1893.

It is also noteworthy that these satellitic syenites are in several ways strikingly different from the early syenites of the border phase of the Vermilion granite. Possibly the alkalic syenites are late differentiates in contrast with the early and more hornblendic syenites.

THE PROCESS OF DIFFERENTIATION

The rock series exhibited by the outcrops of the Vermilion batholith is shown in Figures 10 and 11. Some rock series in other

parts of the world have similar compositions in their end members, as may be seen by the descriptions of the Isle of Skye, Nordingrå, Carrock Fell, St. David's Head, Garabal Hill, and others.[1] None

TABLE VI

ANALYSES OF PHASES OF THE VERMILION BATHOLITH AND SUPPOSEDLY RELATED ROCKS IN MINNESOTA

	1	2	16	8	9	13	14	15	17
SiO_2	71.73	72.06	58.72	57.12	58.55	38.13	5.69	69.01	60.21
Al_2O_3	14.76	16.00	10.81	16.68	12.56	12.20	7.23	16.92	16.28
Fe_2O_3	.58	.46	12.84	1.96	1.72	8.80	46.92	.55	2.49
FeO	1.35	.72	6.80	4.60	5.05	11.68	27.87	1.43	1.62
MgO	.62	.07	.94	4.60	8.03	11.55	3.70	1.28	2.21
CaO	1.18	.86	.82	8.73	7.34	10.35	1.03	2.67	4.76
Na_2O	3.58	4.56	3.59	4.03	3.09	1.39	.28	4.59	3.78
K_2O	4.63	3.54	4.89	1.36	2.01	.43	.24	2.55	6.32
H_2O+	.64	.39	.34	.57	.59	2.36	1.17	.41	.10
H_2O-	.20	.05	.16	.01	.12	trace	.....	trace	.19
CO_2	n. d.	.10	n. d.	trace	.00	trace	.26	n. d.	.47
TiO_2	.53	.12	.42	.39	.51	2.49	5.97	.23	.56
ZrO	.06	.03	.02	.....	.03	trace	(V_2O_5) .49	(ZrO_2) .04	.12
P_2O_5	.14	.09	.20	.33	.14	.19	.02	.11	.23
FeS_2	.06	.09	trace	.08	.04	.33	(S) .12	(S) .04	(S) .03
Cr_2O_3	.02	.02	none	.02	.09	.02	.03	.01	.01
MnO	.03	.06	.08	.14	.17	.30	.26	.03	.08
SrO	n. d.	none	none	.....	.02	.....	(NiO) .09	n. d.	n. d.
BaO	.14	.12	.07	.02	.08	.05	(CoO) .07	(BaO) .03	.30
	100.25	100.24	100.70	100.54	100.65	100.39	101.44	99.90	99.76
Sp. G	2.615	2.637	2.793	2.820	2.820	3.174	4.425	2.670	2.739

1. Vermilion granite, Toscanose from northwest part of Sand Point Lake, Sec. 12, T. 68 N.. R. 17 W.
2. Vermilion granite, Kallerudose, from southeast of Pelican Lake, T. 64 N., R. 19 W.
16. Magnetite pegmatite, Grorudose, from the dump of a shaft in Sec. 3, T. 66 N., R. 17 W.
8. Syenite, Andose, abundant around Basswood Lake.
9. Border phase of granite, Camptonose, near shore of Vermilion Lake, Sec. 30, T. 63 N., R. 16 W.
13. Hornblendite, Auvergnose, north of High Lake.
14. Magnetite ore, V.5.1-4, north of High Lake, J. H. McCarthy, analyst. Recalculated from "Total Fe=55.39, Magnetic Fe=49.28."
15. Biotitic phase of granite Toscanose, that probably assimilated some biotite schist, Gun Lake, Sec. 14, T. 65 N., R. 12 W.
17. Syenite (possibly related to the granite), Monzonose, Linden Township, Sec. 7, T. 62 N., R. 20 W
Analyses by Frank F. Grout, except No. 14.

of these, however, are of batholithic proportions, and it is chiefly in the Cordilleran region of North America that Mesozoic batholiths grading from granite through diorite to gabbro have been well studied.[2] The Vermilion mass, then, adds to the list of batholiths that give a suggestion of their primary magmatic nature, one of the pre-Cambrian masses of the Canadian shield.

[1] Frank F. Grout, "A Graphic Study of Igneous Rock Series," *Bulletin of the Geological Society of America*, Vol. XXXIII (1922), pp. 617–38.

[2] R. A. Daly, *Igneous Rocks and Their Origin*, Appendix B; and Waldemar Lindgren, see *U.S. Geological Survey, Folios 29, 31, 39, 66, 129*, etc.

The primary magma of the Vermilion batholith may have been approximately basaltic in nature, but if so, no specimen collected

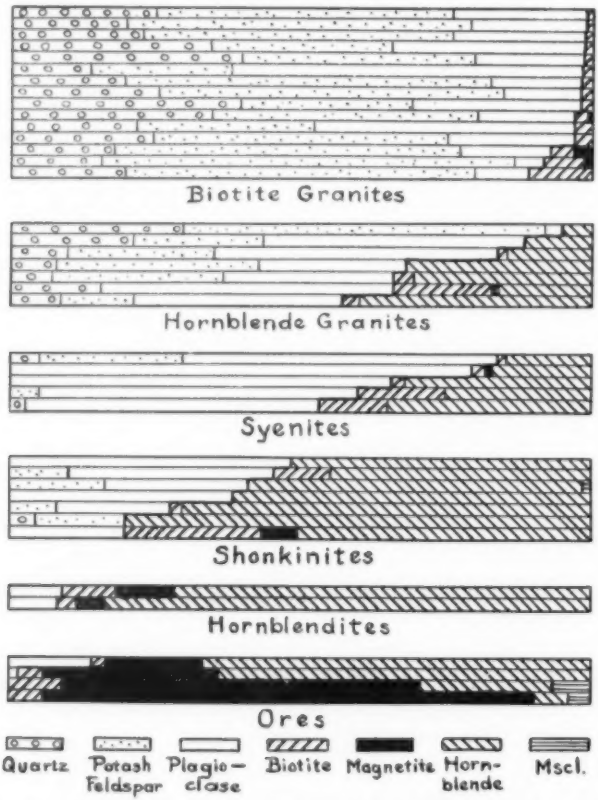

FIG. 10.—Diagram of the modes of the several phases of the Vermilion batholith. Each horizontal bar represents one rock measured. The biotite granites of the upper set make up nine-tenths of the exposures. The plagioclase is acid except in one case, where it is andesine.

represents that magma without a good deal of differentiation. The shonkinite (Basswood type) is probably closest to the composition of primitive basalt,[1] but it has so little alumina that lime is com-

[1] R. A. Daly, *op. cit.*, p. 315.

bined in hornblende, leaving the feldspars alkalic in character. On the other hand, the abundant syenite represented by rock No. 8 is halfway on the course of differentiation to granite. The late stage

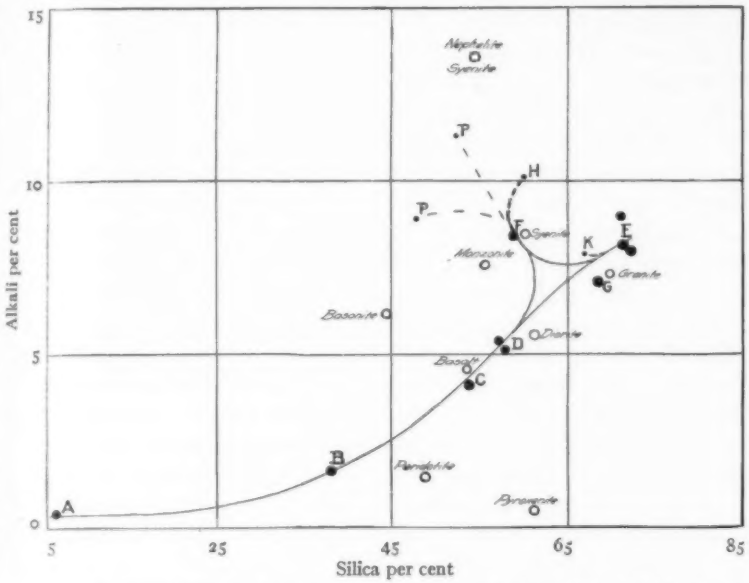

FIG. 11.—A diagram of the rock series of the Vermilion batholith. The black spots show rocks analyzed; the circles show the average compositions of several standard rock families for comparison. The curve marks the general trend of the series; broken lines connect the rocks of the batholith with those of satellites which are probably related. *A*, segregated ore; *B*, hornblendite; *C*, shonkinite; *D*, syenites; *E*, main granite of great extent; *F*, magnetite pegmatite; *G*, granite with assimilated schist; *H*, Linden syenite stock; *K*, Kekequabic granite stock; *P*, Pooh Bah malignite stock.

of magmatic evolution suggested by the abundance of syenite is also indicated by the moderate titanium content of the magnetite segregations—much lower than in common gabbro magnetite, but higher than in the late pegmatites of this same magma.[1]

Whatever the primary magma may have been, the rocks formed here near the top and sides of the batholith do not range from peridotite and normal gabbro to granite, as in the Cordilleran batho-

[1] Frank F. Grout, "Magnetite Pegmatites of Northern Minnesota," *Economic Geology*, Vol. XVIII (1923), pp. 253–69.

liths. They range from hornblendite and magnetite rock through shonkinite and syenite to granite, with only rare traces of feldspar as calcic as andesine. The main portion of the batholith now exposed clearly evolved from its primary composition to a magma of normal granitic nature.

This evolution could not have resulted from syntexis, for the rocks available were not of the right composition. This conclusion is stated with a fair degree of certainty because there are now available analyses of all the main phases of the older rocks. When the magma reached the position where this evolution occurred, the Keewatin greenstone and the Knife Lake slates were the only abundant formations in its roof and walls; there were very subordinate amounts of Soudan iron-bearing rocks, Ogishke conglomerates, and Laurentian intrusives. One of the two major formations, the greenstone, must have had a composition about like that of the primary magma of the batholith and could therefore not cause much change. The other great formation, the Knife Lake slate, is not involved in the development of granite, because, as shown above, the granite has locally assimilated Knife Lake slate, and the change is clearly a decrease in alkalies and silica, with an increase in lime and magnesia. In other words, assimilation changed the granite magma toward a basaltic composition rather than changing some other magma toward a granitic composition.

Since the change in the magma is not logically explained by assimilation or syntexis, differentiation during crystallization may be the most acceptable theory for its evolution. The several border phases then constitute a portion solidified at an early stage while differentiation was in progress.

The banded trachitoid condition of much of this early phase indicates some movement during crystallization. The nearly vertical position of the bands, roughly parallel to the walls of the batholith, is very significant. It can hardly be assumed that this portion of the batholith had a floor on which layers of banded rock accumulated by settling, and that these were later tilted to vertical positions; for batholiths in other regions are not known to have such floors. It is much more reasonable to assume that the bands and wall of the magma chamber are still approximately in their original positions.

The question remains as to what kind of movement produced

the bands and fluxion structure. A batholithic mass, 30 by 80 miles across, stoping its way upward cannot be supposed to develop bands by movements of injection; it could not have been passing through this chamber as magma passes upward in a volcanic plug,[1] though it may have been stirred a little by the settling of stoped blocks. Neither can it be maintained that rhythmic earth movements after the mass was partly crystalline produced a "bridging" or filter pressing that would explain the banding. It is much more likely that a gentle convection circulation was in progress.[2] Any mass of rock crystallized along the walls of a batholith during convection would be in vertical bands as here found, and would show variations in the mineral compositions of the bands, depending on the progress and conditions of cooling—in this case ranging from granite and syenite to shonkinite, hornblendite, and iron ore.

Very little that is definite can be said about the evolution of the alkaline rocks in the five satellitic stocks scattered around the batholith. The location of the stocks about equally distant from the main mass, the development of a sodic pyroxene of about the same nature in three of them, and the occurrence in two of them of shonkinite (Basswood type) like that in the granite batholith, all suggest very strongly a consanguinity with the batholith.

It is noteworthy that while the alkaline bodies, according to theory,[3] are marginal and satellitic, they are not light differentiates which occupy higher positions on account of low specific gravity. Nor is there evidence that the granite was any more deeply eroded than the stocks. Neither mass shows a roof, and all the walls seem nearly vertical. Finally, it should be added that no limestone is available in the region, to explain the alkaline differentiate. The suggestion derived from all this is that the evolution of the alkaline masses may be a primary feature related to the differentiation of the stocks as satellites, rather than a universal development which is accidentally preserved at the points of least erosion.

[1] The vertical banding of Mount Johnson in the Monteregian Hills is so explained by F. D. Adams, *Journal of Geology*, Vol. XI, pp. 278–82.

[2] Frank F. Grout, "Two-Phase Convection in Igneous Magma," *Journal of Geology*, Vol. XXVI (1918), pp. 481–99.

[3] N. L. Bowen, "Later Stages in the Evolution of Igneous Rocks," *Journal of Geology*, Vol. XXXIII (November-December, 1915), Supplement, p. 65.

THE GIANTS RANGE BATHOLITH OF MINNESOTA

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ABSTRACT

The Giants Range batholith is a great body of granite in northeastern Minnesota that lies between the Mesabi and Vermilion iron-mining districts. It outcrops as a narrow belt that strikes east-northeast and occupies an area of about 1,000 square miles. The granite intrudes Archean and Lower-Middle Huronian rocks and is overlain unconformably by Upper Huronian sediments. The Duluth gabbro cut across and metamorphosed its southeastern edge. In general the top of the batholith seems to have been flat except for a row of cupolas which now form the Giants Range. The lateral contacts strike nearly parallel to the adjacent schists. Intrusive effects along the borders include apophysal dikes, marginal breccias, roof pendants, *lit-par-lit* injection, and contact metamorphism. Like most large intrusions, the batholith shows much internal complexity. Hornblende- and biotite-granites, low in quartz and rich in soda, predominate, but variations in mineral composition and texture are numerous. Assimilation of wall rocks probably was slight. Differentiation produced rocks ranging from diabase and shonkinite to soda-granite.

INTRODUCTION

Immediately north of the Mesabi iron range in northeastern Minnesota is a prominent ridge of granite known as the Giants Range. Brief descriptions of parts of the granite have been given previously,[1] and some of it was quarried for paving- and building-stones about 1890, but a general account of the batholith as a whole is lacking. This paper describes the structure, petrography, and petrology of the Giants Range granite and associated rocks in order to meet that deficiency.

The writer is deeply indebted to Dr. F. F. Grout for invaluable suggestions and counsel regarding this paper. Thanks are extended also to Dr. G. A. Thiel for assistance in the field and to Dr. W. H. Emmons for permission to use material of the Minnesota Geological Survey and for reading the manuscript.

GENERAL RELATIONS

Distribution.—The distribution of the granite is shown on the accompanying map, Figure 1. It extends from the vicinity of Grand

[1] N. H. Winchell and U. S. Grant, *Minnesota Geology and Natural History Survey, Final Report*, Vol. IV, chaps. viii–xxi, and accompanying plates. Bibliographies of previous work in the region are available in *U.S. Geological Survey Monographs 43, 45, and 52*. See also other footnotes.

Rapids to a point about 15 miles east of Ely, Minnesota, a total distance of a little more than 100 miles. The ridge of the Giants Range constitutes its southern limit, but in addition the granite occurs in the low-lying plain to the north as much as ten miles from the range. The average width of the granite belt is about 8 miles. Its total area approximates 1,000 square miles.

This belt of granite trends nearly parallel to the strike of the adjoining rocks. It is bordered on the north by the Ely greenstone and Knife Lake slates and on the south chiefly by the Aminikian series of the Mesabi iron-bearing district. The Duluth gabbro cuts across its southeastern edge.

Name, age, and correlation.—The Giants Range granite derives its name from the prominent ridge by that name, whose core is composed almost entirely of it. The granite intrudes[1] rocks as young as Lower-Middle Huronian and is overlain unconformably by Upper Huronian sediments. Structural relations suggest that it was intruded before the crustal movements of mid-Proterozoic time had ceased, though its solidification overlapped these movements. This epoch of pronounced diastrophic and igneous activity has been called Algoman.[2] The Giants Range granite is one of several extensive intrusives of Algoman age in the Lake Superior region.[3] It is correlated with the Vermilion,[4] Kekequabic[5], and Snowbank[6] granites of northeastern Minnesota.

[1] U. S. Grant, *Minnesota Geology and Natural History Survey Annual Report No. 20* (1893), pp. 35–59 and map; J. E. Spurr, "The Iron-bearing Rocks of the Mesabi Range in Minnesota," *Minnesota Geology and Natural History Survey Bulletin 10* (1894), pp. 2–3.

[2] A. C. Lawson, "Archean Geology of Rainy Lakes Restudied," *Geological Survey of Canada Memoir 40* (1913), pp. 5, 108.

[3] A. C. Lawson, "Correlation of the Pre-Cambrian Rocks of the Region of the Great Lakes," *University of California Publications, Bulletin of the Department of Geology*, Vol. X (1916), pp. 1–10.

[4] F. F. Grout, "The Magnetite Pegmatites of Northern Minnesota," *Economic Geology*, Vol. XVIII, pp. 253–54.

[5] U. S. Grant, "Geology of Kekequabic Lake," *Minnesota Geology and Natural History Survey Annual Report No. 21* (1893), pp. 5–58.

[6] J. Morgan Clements, "The Vermilion Iron-bearing District of Minnesota," *U.S. Geological Survey Monograph 45* (1903), pp. 361–64.

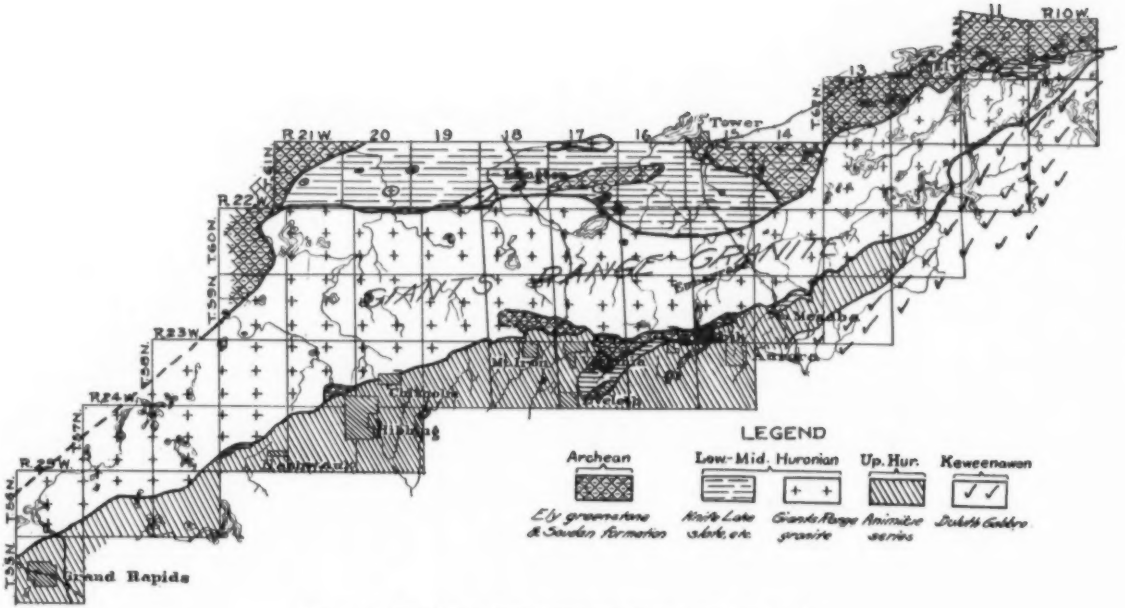

FIG. 1.—Map of the Giants Range granite and associated rocks

STRUCTURE

Intrusive relations.—The general structural relations of the Giants Range granite are shown in Figure 2. At the contact with older rocks the Giants Range granite presents the usual intrusive phenomena such as apophysal dikes, marginal breccias, foreign inclusions, *lit-par-lit* structure, and contact metamorphism. Contact breccias are common along the contact with the Ely greenstone.[1] The fragments are irregular in shape but tend to have rounded corners. At most exposures shattering apparently was closely followed by consolidation, so that solution of the projecting edges and corners was slight. At some exposures fragments of greenstone a few inches wide are so thick in the breccia as to form over half of the rock. South of Ely, xenoliths of greenstone are characteristically small. Hand specimens of granite taken near the contact are thickly studded with roundish aggregates of hornblende crystals, which give the granite a spotted appearance. At a distance from the contact these dark spots become smaller until they grade into xenocrysts of hornblende indistinguishable from crystals that probably formed directly from the magma.

At the contact with the Knife Lake mica-schists the inclusions tend to splinter-like shapes elongate parallel to the schistosity. The shreds of schists vary in length from a few inches to 50 feet or more. Larger peninsula-like projections incompletely separated attain lengths of several rods. *Lit-par-lit* injection commonly occurs in these schistose inclusions as well as in the undisturbed schists.

Along the greater part of the Giants Range from Virginia eastward, the inclusions are slender lenticular bodies. Horizontal exposures reveal lengths of as much as 100 feet; good vertical exposures are limited, but always suggest an equal extension downward. These inclusions stand on edge in the granite parallel to the range, suggesting that at least some of them are the lower tips of roof pendants.

Contact metamorphism.—The Ely greenstone in a belt ½ mile or more in width was converted by the granite to a hornblende rock which is generally schistose.[2] Ellipsoids and to a less extent amyg-

[1] G. M. Schwartz, "Contrast in Effect of Granite and Gabbro Intrusions on the Ely Greenstone," *Journal of Geology*, Vol. XXXII, (1924), pp. 107–8.

[2] J. M. Clements, *op. cit.*, pp. 169–72; C. K. Leith, "The Mesabi Iron-bearing District of Minnesota," *U.S. Geological Survey Monograph 43* (1903), pp. 66–68; G. M. Schwartz, *op. cit.*, p. 103.

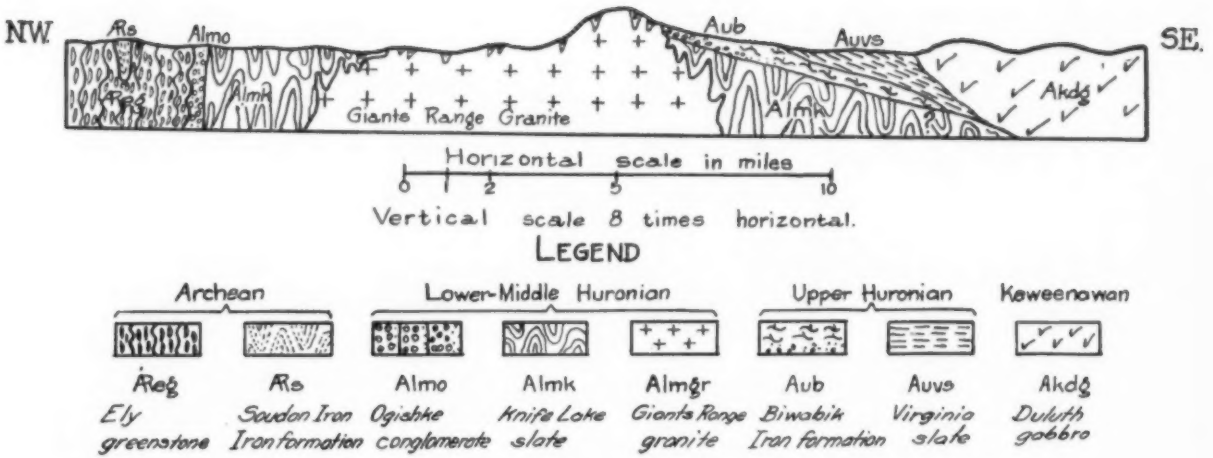

FIG. 2.—Structure section of the Giants Range batholith, somewhat generalized

dules persist into the schists. Hence the recrystallization was accomplished without much horizontal movement, although the orientation of the hornblende crystals in the schists indicates that conditions of differential stress prevailed during their formation. From a comparison of analyses of the hornblende schist and unaltered greenstone, Schwartz concluded that little or no change in chemical composition was produced by the granite.[1]

Granite dikes cut the Soudan iron formation near Ely, and a few small fragments of the formation occur in the contact breccia at White Iron Beach. These fragments are recrystallized to a fine-grained rock of steel-gray color consisting essentially of magnetite and quartz. Inclusions of iron formation occurring in the granite in SW.¼, Sec. 19, T. 57 N., R. 22 W., near Nashwauk, consist of alternating bands composed chiefly of grandular magnetite and quartz or mixtures of the two. Small scales of biotite also are visible. The banding presumably follows the lines of bedding in the original jasper. The recrystallization and coarsening of grain evidently are metamorphic effects of the granite intrusion.

The Lower-Middle Huronian graywacke-slates and associated conglomerates were metamorphosed by the granite to biotite and amphibole schists or granite-gneiss.[2] Occasional garnets appear at the contact. The other common minerals are quartz, feldspar, epidote, actinolite, and muscovite. Sedimentary bands of varying grain and composition remain in the schists. In places near the granite where dikes are abundant, these bands are contorted. Usually the schistosity is parallel to the bedding and nearly vertical. The gneissic phases were formed by *lit-par-lit* injection. The schists weather more readily than the less altered slates or granite, so that topographic depressions are common along the contact with the intrusive.

Ore deposits related to the granite are unknown.

Form of the intrusive.—The Giants Range batholith is a relatively long, narrow body whose longitudinal axis is parallel to the prevailing structure of the wall rocks. The slope of its walls is not clearly revealed by any of the known outcrops, though the slope of the

[1] *Op. cit.*, pp. 104–5.

[2] J. M. Clements, *op. cit.*, pp. 315–17, 340–42, 349–50; C. K. Leith, *op. cit.*, pp. 83–84.

contact along the south side of the Giants Range appears to be rather steep. Along the north side of the granite, a zone of contact metamorphism wider than that along the south side suggests that the north wall is inclined less steeply than the south wall, but the lack of topographic relief prevents direct observation.

The great relative extent of the subsilicic phases of the granite, associated with roof pendants, inclusions, and *lit-par-lit* structure, in the plain north of the Giants Range indicates that the original top of the batholith in that area was at or near the present bed-rock surface. Since this surface is nearly plane, the original top of that part of the batholith probably was nearly flat also.

At some of the gaps in the Giants Range proper, contact features such as inclusions and roof pendants occur down on the sides of the gaps as well as at the top of the range. These remnants of the cover rock suggest that only a thin shell of granite, perhaps less than 100 feet thick, has been removed from some of the hills, and that the deep gaps have been eroded in less resistant schists, leaving the granite standing in domes and ridges. Since subsequent lateral thrust sufficiently intense to produce an uplift of granite like the ridge involved would scarcely be expected to leave contact rocks in the sites of the present steep-sided transverse gaps, these eminences are believed to have been primary elevations on the top of the batholith to which Daly's term "cupola" is applicable.[1] Warping may have accentuated the initial irregularities, but if it had been instrumental in forming the range, dynamic effects would be more common in the granite than they are. Preglacial erosion by streams adjusted to these cupolas is an adequate explanation of the major relief of the Giants Range.[2]

The known cupolas are confined almost entirely to the Giants Range.

Method of intrusion.—*Lit-par-lit* contacts, cleavage in the adjoining schists parallel to the trend of the granite mass, and the

[1] R. A. Daly, *Igneous Rocks and Their Origin* (1914), p. 102.

[2] This structural interpretation of the topography differs from that of Martin, who favored a hypothesis of recent retreat of a protective escarpment of quartzite. "The Physical Geography of the Lake Superior Region," *U.S. Geological Survey Monograph 52*, pp. 104–5.

absence of irregular outlines suggest injection under deep-seated conditions. The elongate form of the batholith, the localization of cupolas in the range, and primary fluxion structure in part of the granite support the view that the magma was squeezed upward into its present position by crustal movements. On the other hand, inclusions of wall rock near the contact indicate shattering and incorporation of fragments of foreign rocks by the rising magma, so that overhead stoping appears to have been a method of intrusion also.

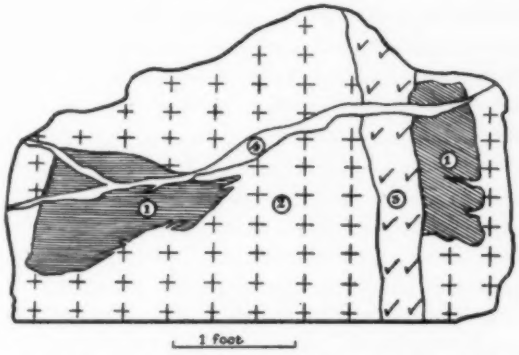

FIG. 3.—Sketch illustrating the succession of intrusives. The lined areas (1) are schist fragments included in dark-gray intermediate granite (2). A dike of granite (3), with abundant bluish quartz, is similar to the Embarrass phase. Aplite (4) cuts all of the earlier rocks. (Redrawn from a photograph.) The same relations are exhibited elsewhere on a much larger scale.

The evidence suggests that the granite formed at a level where both of these processes were operative, i.e., where the zone of fracture grades into the zone of rock flowage.

Internal structure.—The Giants Range granite is not a homogeneous mass, but instead is characterized by a complex succession of multiple phases. Most exposures show more than one phase, and in some places as many as four successive intrusions appear. (See Fig. 3.) Early phases are broken by stringers of aplite, pegmatite, and other dikes, which formed during the course of solidification when portions of the fluid magma penetrated the crust already frozen. These surges brought up material of different composition

according to the degree of differentiation attained in the magmatic chamber.

A trachytoid foliation occurs over wide areas, especially in the early and intermediate phases. Its strike is persistently east-northeast and its dip vertical or nearly so. It may be recognized particularly in the parallel arrangement of subhedral crystals of hornblende, biotite, or feldspar, or combinations of these elongate minerals. This orientation and relative perfection of crystal forms indicate that this foliation is due largely to fluxion. Since the period of crystallization overlapped these movements, the later phases are simply massive and not trachytoid. Foliation due to primary injection occurs at the contacts with schists where *lit-par-lit* structure is present.

Dynamic metamorphism.—Small areas of metamorphic gneiss derived from the Giants Range granite occur at several places, particularly along the south side of the range in a strip usually less than a mile wide. The rocks affected show augen of feldspar in a fine-grained matrix of both light and dark minerals. Subhedral crystals of hornblende, which are common elsewhere in the granite, appear to have been reduced to fine-grained dark streaks in the gneiss, associated with minor amounts of quartz and feldspar. In some places vertical shearing planes are marked by minutely curved micaceous surfaces.

Gneisses formed by pressure subsequent to crystallization are less widespread than those formed by fluxion and injection.

Metamorphism of the granite by Duluth gabbro.—At the contact of the granite with the later Duluth gabbro is a sugar-textured rock in a zone a few feet wide.[1] Under the microscope this contact rock is seen to consist mostly of quartz, acid feldspars, highly pleochroic biotite, augite, and magnetite. Augite makes up 5 to 10 per cent of the rock. It occurs poikilitically as numerous scattered small roundish grains, sparingly as larger ones, as well as in clusters accompanied by biotite and magnetite (or ilmenite). Along the parting in the augite crystals there are microscopic rods and needles of a black metallic nimeral which is probably ilmenite.

[1] C. K. Leith, *op. cit.*, p. 184. These contact rocks were mentioned, but it was not determined whether they were "altered gabbro, altered granite, or an intermixture of the two."

The combination of granitic and poikilitic textures is evidence that the augite and magnetite have formed by recrystallization at the time of the gabbro intrusion, perhaps with slight additions of iron and titanium. The materials may have come entirely from earlier hornblende, chlorite, and biotite.

The principal influences of the gabbro on the granite were: (1) freshening of the feldspars, destroying any previous sericite and kaolin, (2) recrystallization of the ferromagnesian constituents to augite, biotite, and magnetite, and (3) development of minute fractures and veinlets of augite across the feldspar and quartz. These are essentially the same as the effects of the gabbro intrusion upon the Ely greenstones, which Schwartz attributed to the high temperature and relatively anhydrous condition of the gabbro magma.[1]

Faults.—Although faulting has been suggested to explain the topography of the Giants Range, no faults visibly affecting the granite are known. Some minor faults along the Mesabi Range may extend into the granite at depth.

Animikian unconformity.—That the Upper Huronian sediments overlie the Giants Range granite unconformably has been shown by many investigators.[2] Pebbles and bowlders of the granite occur in the basal conglomerate of the Pokegama quartzite and the Biwabik iron formation rather generally. Furthermore, the upper part of the granite at the contact with these sediments shows a zone of pre-Animikie weathering.[3] Later intrusion of the Duluth gabbro metamorphosed an arkosic residuum and conglomerate at the unconformity to a peculiar rock consisting largely of chlorite, quartz, garnet, and amphibole. [4]

[1] *Op. cit.*, pp. 112–21.

[2] Alexander Winchell, "Report of a Geological Survey in Minnesota during the Season of 1887," *Minnesota Geology and Natural History Survey 16th Annual Report* (1888), pp. 357–59; H. V. Winchell, "Report of a Geological Survey in Minnesota during the Season of 1888 in the Iron Regions of Minnesota," *Minnesota Geology and Natural History Survey 17th Annual Report* (1889), pp. 81–96, 128–30; J. E. Spurr, "The Mesabi Iron-bearing Rocks," *Minnesota Geology and Natural History Survey Bulletin 6* (1894), pp. 3–4.

[3] F. F. Grout and T. M. Broderick, "The Magnetite Deposits of the Eastern Mesabi Range of Minnesota, "*Minnesota Geological Survey Bulletin 17* (1919), pp. 6, 53.

[4] A detailed description is in preparation.

PETROGRAPHY

Variations in composition.—The Giants Range batholith is composed of a complex succession of intrusive rocks ranging from diabasic gabbro, hornblendite, and shonkinite through monzonite and syenite to granite. The basic rocks occur in several small scattered masses at the top and sides of the batholith. Granite makes up the bulk of the intrusive inside this discontinuous basic rim. The variations between these extremes take place mostly by gradual transitions in mineral composition. Some abrupt contacts occur where intrusions of the later phases penetrated or even transcended the earlier ones.

The outcrops of basic rocks are too small to be shown separately on the map, since most of them have an area of only a few square rods. One basic phase which outcrops about 10 miles east-southeast of Ely in NE.$\frac{1}{4}$ NW.$\frac{1}{4}$, Sec. 5, T. 62 N., R. 10 W. (accessible only by canoe) is a dark-colored gabbro which grades into the surrounding granite.[1] The transition takes place within about 10 rods without any interruption by dikes, inclusions, or other sharp contacts. The texture is largely granitoid, but locally it is diabasic!

Most of the basic border rocks are hornblendite, shonkinite, or hornblende-syenite, according to the proportions of hornblende and pink feldspar. Some outcrops of these hornblendic rocks a few miles west of Birch Lake lie at the top of the batholith where biotite-schist inclusions are abundant. Other outcrops near Idington, and probable examples near Babbitt, Biwabik, Virginia, and Nashwauk lie at the sides of the batholith. Since they consist so largely of hornblende, they resemble that part of the Ely greenstone which was metamorphosed by the Giants Range granite. However, in several cases they clearly are intrusive and constitute a part of the batholith, as shown by the following relations: (1) They occur at contacts of the granite with rocks other than greenstone. (2) Some of them contain inclusions of Knife Lake schists, in fact they usually are associated with the schists. (3) They grade into hornblende-syenites—

[1] Reported by U. S. Grant, *Minnesota Geology and Natural History Survey 20th Annual Report* (1892), pp. 41–42; by N. H. Winchell, *Minnesota Geology and Natural History Survey 24th Annual Report* (1899), p. 67; and confirmed in September, 1924, by Dr. F. F. Grout and the writer.

such variation even within the space of a few feet is rather characteristic. (4) Where they are cut by later intrusions, the contacts are usually vague and indefinite with feathery edges, probably because the rocks were still hot, whereas dikes into the Ely greenstone generally have sharp outlines. (5) By analogy, similar basic borders occur about other Algoman granites of Minnesota, notably the Vermilion granite. (6) Furthermore, in a negative way, no such masses of coarse hornblende rock of any considerable size are known along the contact with the Ely greenstone where they might be expected if they were due to metamorphism. In view of their composition and structural relations, they are regarded as differentiates which crystallized relatively early.

The prevailing rock in some large areas at the edge of the batholith, however, is not the basic phase, but a monzonite, hornblende-syenite, or granite. Although granite predominates, considerable masses contain little or no quartz, and some others contain andesine, and so, to avoid confusion with the other granites, the general mass at the border may be conveniently designated "intermediate." This phase is probably more extensively exposed than any other. The principal exposures are: (1) in the Kawishiwi-Birch River area, (2) in the area southwest of White Iron Lake, almost to Embarrass, (3) at the west end of the Giants Range, between Hibbing and Grand Rapids, (4) in the plain northwest of Mountain Iron, and (5) in the Giants Range proper between Virginia and Mesaba, where it is typically developed. On account of the widespread presence of inclusions, this phase appears to have crystallized at or near the original roof and border of the batholith.

This intermediate phase is cut extensively by dikes of aplite, pegmatite, the Embarrass phase, and other later rocks. Subsequent invasions of this sort may be seen at nearly every large outcrop.

Although Grout and Broderick[1] showed that the granite named Embarrass by Leith[2] is really a part of the Giants Range granite as previously mapped by Winchell,[3] the name is retained here to dis-

[1] *Op. cit.*, p. 8.

[2] *Op. cit.*, p. 186.

[3] N. H. Winchell, *Geology and Natural History Survey of Minnesota, Final Report*, (1899), Vol. IV, Pl. 67.

tinguish a coarse red granite phase, characterized by abundant large grains of bluish quartz. The Embarrass granite phase outcrops principally in the core of the Giants Range for a distance of about 12 miles southwest of Birch Lake. A disconnected outcrop occurs at Embarrass station on the Duluth and Iron Range Railway. Dikes of the Embarrass phase cut the darker-gray intermediate phase at Birch Lake[1] and at other places to the west of it. (See Fig. 3.) It therefore crystallized later than the intermediate phase, but since unmistakable fragments of it occur in the conglomerate at the base of the Animikie series, it certainly is pre-Animikie and not as late as Keweenawan in age Its coarseness, late crystallization, and abundant fluid inclusions in its quartz are best interpreted as results of its structural position in the core of the batholith. The local approach in mineral composition of the Embarrass phase to the intermediate rocks suggests a gradual transition between them in the body of the batholith where the relations are not interrupted by dikes.

A biotite-granite phase outcrops extensively (1) in the Giants Range between Mountain Iron and Chisholm, and (2) near the north side of the batholith southwest of Idington. It may be significant that these two belts occur on the flanks of the widest portion of the batholith. The southern belt is cut off at its eastern end by schists near Mountain Iron and is concealed at its western end by drift. Accessory hornblende exceeds biotite near Chisholm and near Virginia, so that there seems to be a gradual transition to the intermediate hornblende-granites which occur to the west, north, and east of it. The northern belt, though nearly isolated by drift, shows similar transitions. The composition of the biotite-granite phase implies prolonged differentiation, which suggests that it crystallized later than the less siliceous rocks around it. Its resemblance to biotitic dike rocks which cut the intermediate rocks elsewhere supports this interpretation.

Apophyses of the batholith include the usual aplites and pegmatites, rhyolite- and granite-porphyry dikes.[2] small schistose basic

[1] C. K. Leith, *op. cit.*, p. 188.

[2] U. S. Grant, *Minnesota Geology and Natural History Survey 20th Annual Report* (1893), pp. 35–59; J. Morgan Clements, *op. cit.*, atlas; C. K. Leith, *op. cit.*, pp. 78–90.

dikes in the Knife Lake slates, and larger masses of shonkinite and granite north and northwest of the main area. These satellites at the northwest are like stepping-stones in the gap between the Giants Range and Vermilion batholiths, both of Algoman age.

Gabbro phase.—The gabbro consists of about 70 per cent labradorite and 30 per cent hornblende. In the center of many of the grains of hornblende are cores of augite. This relationship indicates that the hornblende is secondary and pseudomorphous. In some specimens the hornblende surrounds the laths of labradorite in the manner of a diabase, but in others the diabasic texture is absent. Magnetite and apatite are minor accessories. Chlorite, sericite (probably paragonite), kaolin, epidote, pyrite, and leucoxene are alteration products.

Other specimens in a transitional series contain hornblende, pseudomorphous after augite, plagioclase ranging from albite to andesine, and traces of diabasic texture obscured by a small quantity of interstitial quartz and orthoclase. With increasing amounts of orthoclase, quartz, and acid plagioclase, the rocks grade into the prevailing granite of the region.

The augite and plagioclase show reaction rims, but the changing character of the rocks probably is due largely to differentiation. The diabase may be interpreted as a portion of the magma which was chilled at the border of the batholith before differentiation had progressed very far. Its composition therefore should approximate that of the primary magma. Its basic character is a strong indication that the primary magma was basaltic.

Shonkinite phase.—The shonkinite is composed essentially of green hornblende and acid feldspars, with unusually large amounts of apatite and titanite and lesser amounts of magnetite and zircon as accessories and inclusions. The texture as a whole is granitoid. The hornblende occurs in large irregular grains, many of which show cores of augite. These rims of hornblende probably are due to magmatic reaction with earlier crystals of augite. Hornblende (including augite) constitutes as much as 90 per cent of some specimens. The feldspars in order of abundance are acid plagioclase, microcline, orthoclase, and microperthite. Some of them in the form of phenocrysts inclose small euhedral crystals of hornblende as poikilitic in-

clusions. Chlorite, sericite, etc. indicate hydrothermal alteration to a moderate degree.

Intermediate phase.—The intermediate phase is a dark pinkish-gray, medium-grained, trachytoid porphyritic rock, consisting essentially of quartz, oligoclase (or albite), orthoclase, and microcline. Hornblende or biotite, or both, magnetite, ilmenite, titanite, apatite zircon, primary epidote, allanite, tourmaline, augite, and garnet, and alteration products including chlorite, sericite, muscovite, kaolin, leucoxene, epidote, carbonate, and pyrite commonly are present in small amounts.

Quartz is absent in some places, but it averages 17 per cent of the rock and is at least 28 per cent of some exposures. It occurs usually in very small grains a fraction of a millimeter in diameter, which commonly are associated with micrographic intergrowth to form a matrix for the other minerals.

The total feldspar constitutes about 68 per cent of the rock, averaging 35 per cent plagioclase, 26 per cent orthoclase, and 7 per cent microcline. In the specimens examined, the amount of plagioclase varies between 15 and 50 per cent, and orthoclase between 12 and 33 per cent. Microcline is absent in some specimens and reaches an observed maximum of 15 per cent in others, usually with a corresponding reduction in the quantity of orthoclase. The orthoclase and plagioclase tend to form blocky crystals about 2 or 3 millimeters in diameter. Perthitic combinations appear in some cases. The plagioclase is usually oligoclase and less often albite. Zonal growth is common, so that the interiors of some crystals probably are as basic as andesine, but hydrothermal alteration, which is greatest at their centers, makes difficult an exact determination by optical methods. Notable amounts of normative anorthite, however, seem to confirm the presence of some andesine in the more basic specimens. The feldspars include numerous small grains of hornblende, biotite, titanite, apatite, magnetite, and ilmenite.

The phenocrysts of feldspar commonly are 2 to 5 centimeters long. Their chemical composition is shown by the analyses in Table I.

Of the mafic constituents, common green hornblende is most characteristic, but green or brown biotite is generally present and

in some cases is the only mafic mineral. In the intermediate phase, the maximum amount of hornblende measured is 19 per cent, and of biotite 8 per cent, the average for each being 8 and 5 per cent respectively. The total mafic minerals in this phase usually do not exceed 24 per cent of the rock, or about twice the average. The hornblende crystals are subhedral in outline and commonly 3 to 5 millimeters long. Biotite occurs in long, irregular shreds or tufted aggregates. Inclusions of titanite, rutile, apatite, zircon, and ilmenite or magnetite are common in hornblende and biotite. Leucoxene, green or brown chlorite, epidote, and muscovite appear as alterations of the combination. In a few cases subhedral grains of epidote are so intergrown with hornblende, quartz, and feldspar that they are regarded as primary. Allanite was seen in four specimens. Augite is reported to occur in the granite near Mallman camps in T. 59 N., R. 14 W.[1] Of the less abundant accessory minerals, titanite is most common, followed by apatite and zircon in order.

TABLE I*

ANALYSES OF FELDSPAR PHENOCRYSTS

	I	II
SiO_2	65.12	65.72
Al_2O_3	18.32	18.45
Fe_2O_3	1.89	1.93
MgO	.04	.22
CaO	.98	.61
Na_2O	9.35	8.86
K_2O	3.18	3.14
H_2O	.22	.20
	99.10	99.13

* These analyses were found in unpublished notes of A. H. Elftman, of the Minnesota Geology and Natural History Survey, dated August 8, 1898.

I. A single crystal from the Giants Range granite on the north shore of Birch Lake, T. 62 N., R. 11 W. H. B. Hovland, analyst.

II. Composite sample of 10 crystals from the same locality. H. B. Hovland, analyst.

Embarrass phase.—The Embarrass phase is a red, coarse-grained hornblende-granite characterized by large and abundant grains of

[1] C. K. Leith, *op. cit.*, p. 78.

blue quartz. These blue quartz crystals are as much as a centimeter or more in diameter. A few extra-large crystals of microcline and plagioclase and an occasional blade of hornblende make the rock porphyritic. The rock consists of acid plagioclase, orthoclase, quartz, microcline, and minor amounts of hornblende, biotite, ilmenite, magnetite, titanite, zircon, and apatite, usually in the order named. Chlorite, sericite, epidote, etc. appear in small amounts as alterations of these minerals.

The quartz in thin section is colorless rather than blue and contains innumerable microscopic inclusions of zircon, apatite, and fluids arranged in lines and irregular streaks variously oriented. The blue color of the quartz in the hand specimen is probably due to these inclusions. There are traces of micropegmatite between the larger crystals.

The proportions of the feldspars vary within wide limits. Orthoclase may be more or less abundant than microcline or plagioclase. A specimen obtained near Babbitt contains 45 per cent plagioclase, 22 per cent microcline, and only 13 per cent orthoclase, thereby approaching the composition of the intermediate phase, though retaining the distinctive blue quartz. The plagioclase shows distinct zonal growth, with cores of oligoclase surrounded by rims of albite. Central alteration of the plagioclase crystals is common, so that twinning bands are obscure and the mineral easily mistaken for orthoclase.

Common green hornblende occurs in long, slender euhedral crystals. Some crystals are entirely inclosed in large grains of feldspar. Biotite is sparingly present in some places as characteristic elongate flakes. Euhedral crystals of ilmenite, magnetite, titanite, zircon, and apatite are common inclusions in all the other minerals. "An occasional crystal of andalusite, and perhaps also tourmaline and garnet" are reported by Leith.[1]

Biotite-granite phase.—The biotite-granite phase is a pale pinkish-gray, medium-grained granite consisting essentially of albite, quartz, orthoclase, and microcline, in the order named. The accessory minerals are biotite, muscovite, hornblende, magnetite, titanite, apatite, and zircon. Alteration products include sericite, chlorite,

[1] *Op. cit.*, p. 187.

leucoxene, kaolin, and limonite stains. The texture is hypautomorphic, but the size of grain is somewhat variable.

Quartz occurs in small, irregular interstitial grains and in small patches of graphic intergrowth with orthoclase and albite. Some of

TABLE II

ANALYSES

	A	B	C	D	E	F	G	H	I	J
SiO_2	47.27	50.27	49.65	52.24	54.57	60.42	66.31	69.70	71.45	72.39
Al_2O_3	6.99	7.61	9.27	11.66	17.91	12.28	12.70	18.72	12.99	13.39
Fe_2O_3	3.10	2.86	5.00	2.33	2.68	5.57	1.98	0.65	2.44	0.18
FeO	5.44	7.04	6.08	8.48	4.80	4.32	2.66	0.79	1.78	1.44
MgO	9.18	7.92	8.89	9.78	3.86	3.40	3.01	0.45	0.84	1.61
CaO	20.49	13.87	13.08	9.41	6.01	4.95	4.77	2.25	0.65	0.92
Na_2O	1.91	2.41	2.38	1.94	4.69	4.50	5.03	5.01	6.96	5.35
K_2O	0.89	3.63	1.71	0.87	2.34	2.02	2.33	1.68	1.25	2.42
H_2O+	1.28	0.84	1.71	1.26	1.68	1.42	0.75	0.71	1.24	1.22
H_2O-	0.04	n.d.	0.28	0.14	0.06	0.08	0.05	n.d.	0.10	0.02
CO_2	tr.	none	tr.	none	none	none	n.d.	n.d.	n.d.	n.d.
TiO_2	0.67	1.51	0.89	1.42	0.20	0.74	0.49	n.d.	0.13	0.49
ZrO_2	0.01	0.26	0.05	n.d.	0.07	0.07	0.06	n.d.	0.10	0.15
P_2O_5	1.62	1.46	0.06	tr.	0.11	0.20	0.13	n.d.	0.04	0.10
S	0.01	none	tr.	0.01	0.04	0.02	tr.	n.d.	tr.	none
Cr_2O_3	none	0.03	0.04	0.08	none	none	0.01	n.d.	0.02	none
MnO	0.30	0.20	0.56	0.12	0.14	0.06	0.04	n.d.	0.04	0.01
BaO	0.08	none	0.16	0.08	0.11	0.07	none	n.d.	none	none
SrO	.....	.....	0.12	.....	.....	.....	.....	.....	.....	.....
	99.28	99.91	99.93	99.77	99.27	100.12	100.32	99.96	99.97	99.69

A. Shonkinite, from Idington. I. S. Allison, analyst.

B. Porphyritic shonkinite, from Idington. R. J. Leonard, analyst.

C. Shonkinite (Basswood type), Sec. 21, T.61 N., R.21 W. I. S. Allison, analyst.

D. Gabbro, NE.¼, NW.¼, Sec. 5, T.62 N., R. 10 W. I. S. Allison, analyst.

E. Monzonite, NW.¼, Sec. 7, T. 61 N., R. 12 W. I. S. Allison, analyst.

F. Hornblende-granite, Hinsdale quarry, Sec. 17, T. 59 N., R. 17 W. R. J. Leonard analyst.

G. Hornblende-biotite-granite, Sec. 28, T. 59 N., R. 17 W. I. S. Allison, analyst.

H. Prophyry dike, 50 feet wide, W.½, NE.¼, Sec. 21, T. 63 N., R. 10 W. A. D. Meeds, analyst. U. S. Grant, *Minnesota Geology and Natural History 20th Survey Annual Report* (1892), p. 57; and *21st Annual Report* (1893), p. 43.

I. Biotite-granite, Sec. 31, T. 59 N., R. 18 W. R. J. Leonard, analyst.

J. Embarrass granite, from Embarrass station. R. J. Leonard, analyst.

the crystals of feldspar are euhedral in outline. A few grains of feldspar are perthitic. Phenocrysts are sparse. The accessory minerals to a large extent are included within the feldspars and usually do not exceed 5 per cent of the rock. At least a part of the muscovite is

secondary after biotite. Nearly colorless chlorite has replaced both biotite and hornblende extensively, and some sericite appears in the albite. Halos appears around zircon in the biotite, and fringes of leucoxene on biotite are common. Titanite, apatite, and magnetite are scattered through the rock as small inclusions.

CLASSIFICATION

In the C.I.P.W. quantitative classification, rocks A and B are Brandbergose, C is Kilauose, D is Kentallenose, E is Andose, F and G are Dacose, H is Lassenose, and I and J are Kallerudose. Of these ten rocks, six are at least dosalic, eight at least quardofelic, six at least domalkalic, and seven are dosodic.

In Johannsen's table[1] the rocks would be classified on the basis of mineral composition as follows:

A melamonzonite	F adamellite (quartz monzonite)
B mela-albite-syenite	G monzo-granite
C gabbro	H leuco-albite-adamellite
D melasyenite	I albite-adamellite
E monzonite	J adamellite

The prevailing rock in the batholith is a hornblende- or hornblende-biotite-granite. Syenitic portions are local. According to the classification of Johannsen, the main rock would be called an adamellite (quartz monzonite) on account of the abundant oligoclase.

The term "monzonite" properly will apply only to the rocks with a mixture of andesine and orthoclase, whereas in the Giants Range rocks most of the plagioclase is not as calcic as andesine. The same objection applies to the use of the name "adamellite." The terms "monzonite" and "adamellite" therefore are somewhat misleading in this case unless qualified by a descriptive prefix such as "albite-" or "oligoclase-." Notwithstanding an abundance of plagioclase (usually oligoclase), the rocks as a whole are chemically allied more closely to granite than to monzonite or quartz-monzonite.

ASSIMILATION

Hornblende normally is more abundant in the granite near the contact, but the extent to which it represents materials derived from

[1] Albert Johannsen, "A Quantitative Mineralogical Classification of Igneous Rocks —Revised," *Journal of Geology*, Vol. XXVIII (1920), pp. 36–60, 158–77, 210–32.

the wall rocks is uncertain. Some inclusions of Ely greenstone, recrystallized to hornblende rocks, have roundish forms which suggest solution of the projecting edges and corners. The extent of such solution, however, appears to have been small, since numerous inclusions are angular or nearly so. In connection with *lit-par-lit* injections into

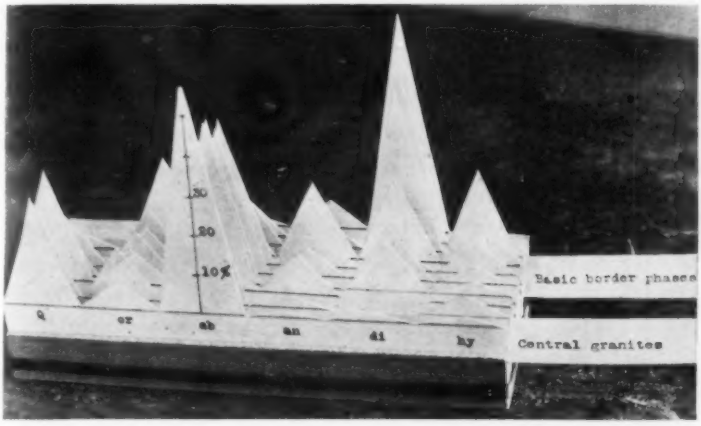

FIG. 4.—Photograph of a model showing the proportions of the six principal normative minerals in the ten rocks whose analyses are given in Table II. In the model ten cards, each representing an individual rock, are arranged in order of increasing normative albite. The height of the peaks according to the scale shown indicates the amount of each constituent in the norm. The proportional increases in normative albite and quartz are accompanied by decreases in anorthite, diopside, and hypersthene. (This is a modification of the method described by Dr. F. F. Grout, "A Form of Multiple Rock Diagrams," *Journal of Geology*, Vol. XXVI [1918], pp. 622–25.)

schists, assimilation is a recognized phase of the process of granitization. The *lit-par-lit* zones at the contact of the Giants Range granite generally range from a few feet to several rods in width. The granite inside this narrow zone shows no apparent hybridism. On the whole it appears that the amount of assimilation is limited.

DIFFERENTIATION

The rocks of the Giants Range form a series showing progressive changes in mineral and chemical composition in order of their crystallization. In terms of rocks, the determinable variation is from

gabbro and shonkinite through hornblende-syenite (monzonite or adamellite) to granite. The early basic phases, shown by the cards at the back in Figure 4, are characterized by abundant diopside, moderate amounts of hypersthene and anorthite, and small amounts of albite and orthoclase. In contrast with these, the late granites (in front) contain abundant albite and quartz and extremely little anorthite, diopside, or hypersthene. Between the two extremes there is a nearly complete gradation (Fig. 5). A peculiar feature of the series is the nearly constant amount of orthoclase.

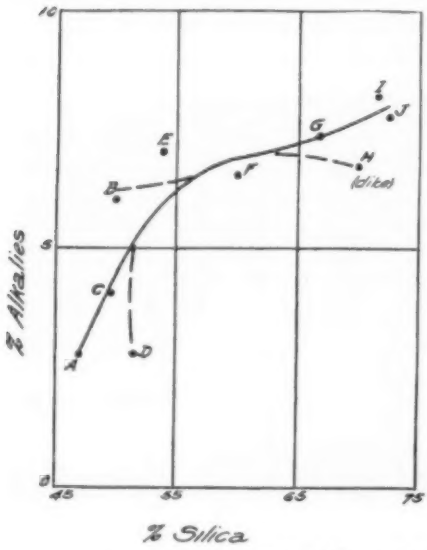

FIG. 5.—A chart of the differentiation in the Giants Range batholith. The dots represent individual analyses, the letters corresponding to those in Table II. The range is from rocks low in silica and alkalies at the lower left to alkalic (sodic) granites at the upper right. The heavy line, or axis, is added to show the general trend.

Since there is no evidence to show that the variation in this series is due to assimilation, syntexis, or fractionation of liquids, the generally accepted method of differentiation by crystal-settling probably is the proper explanation of the series.

A minor result of differentiation was the formation of small knots, bunches, and schlieren, composed of hornblende, biotite, or magnetite, that probably should be regarded as segregations.

AMOUNT OF ASSIMILATION BY THE SUDBURY NORITE SHEET

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ABSTRACT

Assimilation has long been recognized as a process associated with all large intruded or injected masses. The following article attempts to show that the Sudbury norite magma has assimilated an amount of rock equivalent to two-thirds of its original volume and possibly as much as two to three times that amount.

INTRODUCTION

Nearly all geologists who have studied large intrusive or injected masses of rock have been impressed by the presence of indefinitely outlined fragments of rock foreign to the body in which they occur. Reaction has so changed their chemical composition and mineralogical character and structure that only the large features of the xenoliths are preserved in ghostlike outlines of their former selves. The problem arises, to what extent have blocks, similar in original character to these ghosts, been completely dissolved and reprecipitated by the invading magma, and what effect have they produced upon the final composition of the magma solution.

The author made a number of analyses of specimens of rock types from the basal part of Sudbury norite sheet in its prolongation north of the Spanish River (Fig. 1). It was necessary to use analyses made by other authors who have studied the micropegmatitic portion of the sheet, in order to show the variation of the sheet from the base to the top. The curves are, therefore, not across a single section, but represent an average of the southern edge of the injective. All the analyses were plotted on curves, and it became strikingly apparent that there was more silica in the present norite sheet than was a constituent part of the original magma solution. This discrepancy immediately led the author to study the analyses more carefully, keeping in mind a simple differentiating magma and its behavior.

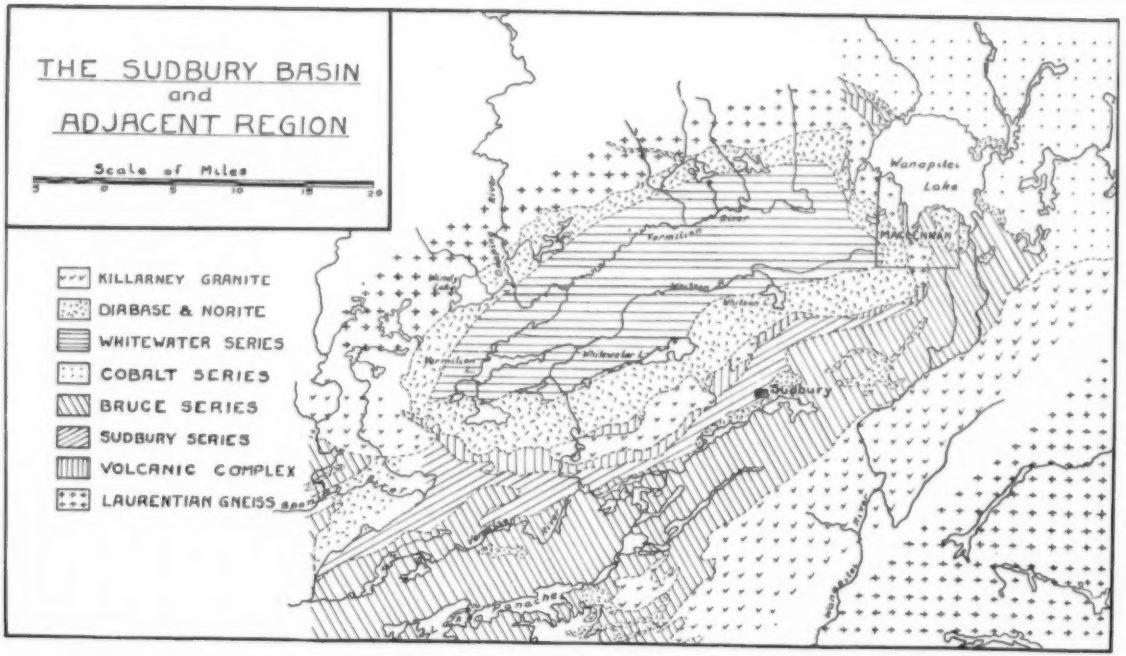

FIG. 1.—Map of the Sudbury Region

THEORY OF SIMPLE DIFFERENTIATING MAGMA

The base of the norite sheet is distinctly finer grained than that portion lying 100 feet or more above. Zoned pyroxenes and other structures due to rapid crystallization or "chilling" are very characteristic. This basal margin ought, therefore, to represent a sample

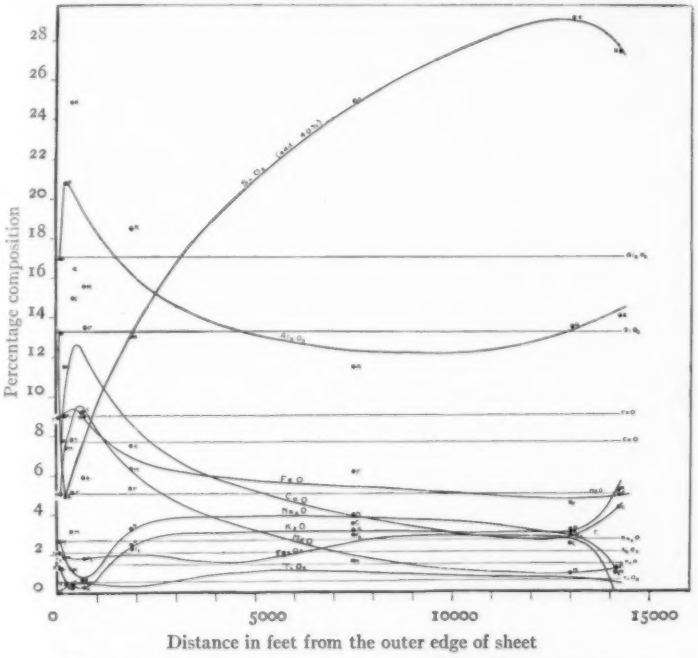

FIG. 2.—Graphic representation of analyses compiled by the author

of the parent magma injected as a sheet between the overlying Animikie series and the underlying Sudbury series. The sheet becomes progressively less salic for some hundred feet above the "chilled" basal edge, until the silica reaches a minimum, after which the salic components increase very rapidly. Then if differentiation were the only operative process, the deficiency of any constituent in the mafic (basal) part of the sheet should be equal to the excess of the same material in the salic part of the sheet. Any difference must be due

to some outside influence, which might behave in two ways: first, some constituents might be added; secondly, some constituents might be subtracted, or some might be added and others subtracted, following the crystallization of the basal chilled margin. Any constituents subtracted would be held in metamorphic minerals in the contact zones above and below the sheet. The contact zones are very narrow being from 100 to 500 feet wide, and represent a very slight

TABLE I

Composition of Basal or "Chilled" Edge

	1	2	3	4	5	6
SiO_2	49.10	49.90	56.89	54.84	51.20	52.39
Al_2O_3	17.04	16.32	19.39	15.82	17.32	17.18
Fe_2O_3	1.54	.....	0.38	3.36	5.04	2.06
FeO	8.95	13.54	7.11	7.02	9.06	9.14
CaO	10.80	6.58	8.11	5.71	6.76	7.59
MgO	6.56	6.22	2.11	6.02	4.14	5.01
K_2O	0.61	2.25	1.04	2.31	2.14	1.67
Na_2O	1.91	1.82	3.31	3.87	2.32	2.65
H_2O+	1.28	0.76	1.35	1.27	2.15	1.38
H_2O-	0.11					
TiO_2	0.26	1.47	0.43	Not deter.	Not deter.	0.72
CO_2	1.30	Not deter.	Not deter.	Trace	0.25	0.31
MnO	Not deter.	Trace	0.30	Not deter.	Not deter.	0.30
Total	99.46	98.86	100.53	100.22	100.38	100.40

1. Basal part of norite sheet at Savage Lake. Analyst, G. W. Bain.
2. Basic edge on southern range, Blezard Mine. Analyst, T. L. Walker.
3. Basic edge on northern range near Onaping, includes P_2O_5, 0.11 per cent. Analyst, E. G. R. Ardagh.
4. Basic edge at Murray Mine. Analyst unknown.
5. Basic edge at Evans Mine. Analyst unknown.
6. Average of analyses of lower margin of norite sheet.

change in the original chemical composition of the rocks. When the thickness of the sheet (7,000 to 14,000 feet) is compared with the width of the contact zones (100 to 500 feet), it is apparent that the change in chemical composition in the contact zone would have to be very great to represent any appreciable subtraction of material from the norite magma to bring about this change. Therefore, the amount of material subtracted from the magma can be neglected in the following calculations of the changes in composition, and all the changes can be considered to be brought about by addition of material from the outside.

TABLE II

ANALYSES ACROSS NORITE SHEET

	1	2	3	4	5	6	7	8	9	10	11	12	13	14
SiO_2	49.10	44.90	45.80	48.51	47.83	45.38	48.02	45.91	49.90	53.34	53.08	64.85	69.27	67.76
Al_2O_3	17.04	20.92	10.59	29.63	24.87	7.09	17.91	9.25	15.35	14.39	18.54	11.44	12.56	14.00
Fe_2O_3	1.54	1.47	1.50	0.09	0.44	1.89	1.30	1.77	1.01	1.44	2.26	2.94	2.89	.....
FeO	8.95	9.11	14.50	2.00	5.12	14.29	9.92	13.42	9.65	11.69	5.28	6.02	4.51	5.18
CaO	10.80	11.55	12.42	15.90	15.03	8.90	10.88	9.30	12.44	7.84	7.51	3.49	1.44	4.28
MgO	6.56	7.44	10.88	0.50	3.09	17.50	7.91	15.58	8.30	5.50	6.18	1.60	0.91	1.00
K_2O	0.61	0.66	0.27	0.34	0.32	0.27	0.80	0.37	0.56	0.64	2.41	3.02	3.05	1.19
Na_2O	1.91	1.82	1.24	1.23	1.23	0.33	1.93	0.72	2.08	1.90	3.35	3.92	3.12	5.22
H_2O+	1.28	1.23	1.54	0.69	0.90	4.43	1.74	3.89	0.85	1.21	1.41	0.78	0.76	1.01
H_2O-	0.11	0.16	0.10	0.12	0.11	0.00	0.25	0.05	0.09	0.05				
TiO_2	0.26	0.56	1.81	0.68	0.96	0.65	0.44	0.61	0.96	1.05	Not deter.	.....	0.78	0.46
CO_2	1.30	0.52	.....	0.67	0.50	.....	.....	.....	.....	0.53	Trace	Not deter.	Not deter.	Not deter.
Total	99.46	100.34	100.65	100.46	100.40	100.73	101.10	100.87	101.26	99.58	100.02	98.30	99.35	100.29

1. Chilled margin of norite sheet, west of Savage Lake. Analyst, G. W. Bain.
2. 100 feet above No. 1. Analyst, G. W. Bain.
3. 200 feet above No. 2. Dark portion of orbicular norite. Analyst, G. W. Bain.
4. 200 feet above No. 2. Light portion of orbicular norite. Analyst, G. W. Bain.
5. Average of Nos. 3 and 4 taking volume into consideration.
6. Dark portion of banded norite 300 feet above Nos. 3 and 4. Analyst, G. W. Bain.
7. Light portion of banded norite 300 feet above Nos. 3 and 4. Analyst, G. W. Bain.
8. Average of Nos. 6 and 7 taking volume into consideration.
9. Diabase dyke cutting roof of the norite sheet in Vernon Township. Analyst, G. W. Bain.
10. Diabase duke cutting roof of the norite sheet in Nairn Township. Analyst, G. W. Bain.
11. 1900 feet northwest of basic edge Murray Mine. Analyst unknown.
12. Middle of Blezard-Whitson Lake Section. P_2O_5, 0.24 per cent; MnO, trace. Analyst, T. L. Walker.
13. Near Acid Edge, Blezard-Whitson Lake Section. P_2O_5, 0.06 per cent; MnO, trace. Analyst, C. B. Fox.
14. Acid Edge, Blexard-Whitson Lake Section. P_2O_5, 0.19 per cent; MnO, trace. Analyst, T. L. Walker.

(The basal part of the sheet shows very great original variation in chemical ocmposition, so that it was necessary to average the composition, taking volume into consideration, in the case of the orbicular and the banded norites.)

DETERMINATION OF DIFFERENCES

The difference in composition between the average original magma and the average final composition of the sheets is determined from the curves. The ordinates of the curves represent percentage, and the abscissae distance from the base. Then the area between the curve and the base divided by the length of the base gives the average composition of the final magma solution. The original composition of the magma solution is given by the composition

TABLE III

ACTUAL AND ANTICIPATED AVERAGE COMPOSITION OF NORITE

	1	2	3	4
SiO_2	52.39	53.28	62.27	+8.99
Al_2O_3	17.18	17.45	14.28	−3.19
Fe_2O_3	2.06	2.07	2.08	+0.01
FeO	9.14	9.29	5.99	−3.30
CaO	7.59	7.71	5.32	−2.39
MgO	5.01	5.08	3.11	−1.97
K_2O	1.67	1.69	2.70	+1.01
Na_2O	2.65	2.69	3.52	+0.83
TiO_2	0.72	0.73	0.73	0.00
Total	98.41	100.00	100.00	+0.01

1. Anticipated average content of principal constituents.

2. Anticipated average content of principal constituents corrected to 100 per cent (H_2O and CO_2 excluded).

3. Actual average content of principal constituents determined from the calculations.

4. Difference between actual and anticipated percentage.

of the chilled lower margin. The analyses used in plotting the curves (Fig. 2) are given in Tables I and II.

The difference between the original and final composition, determined in the manner previously outlined, is given in Table III. Evidently some constituents have been added in very much larger amounts than others. Then it is necessary to determine the relative percentage change in each of the constituents in order to determine which constituent has been increased by the smallest amount.

$$\text{Relative percentage change} = 100 \times \frac{(\text{Final composition} - \text{original composition})}{\text{original composition}}$$

The figures used and mathematical results are set forth in Table IV. Then the constituent which has been added in least amount is that which shows the greatest negative relative percentage change. (Negative relative percentage change would ordinarily indicate that those constituents had been subtracted from the magma solution, but since it has been shown that the amount of material removed from the solution is negligible in amount, the subtraction is apparent rather than real, and is due to predominant

TABLE IV

RELATIVE PERCENTAGE CHANGE

	Final Composition Less Original Composition	÷	Original Composition	=	Relative Change Percentage
SiO_2	+8.99	÷	53.28	=	+16.89
Al_2O_3	−3.17	÷	17.45	=	−18.19
Fe_2O_3	+0.01	÷	2.07	=	+ 0.48
FeO	−3.30	÷	9.29	=	−35.55
CaO	−2.39	÷	7.71	=	−30.10
MgO	−1.97	÷	5.08	=	−38.75
K_2O	+1.01	÷	1.69	=	+59.15
Na_2O	+0.83	÷	2.69	=	+30.82
TiO_2	0.00	÷	0.73	=	0.00
Total	+0.01		100.00		.....

additions of the positive components.) The least amount of any component which it is possible to add is none whatsoever. Magnesia is the component which has been added in least amount. Imagine that no magnesia has been added; then the following calculation of the dilution factor for the magma becomes possible:

$$\frac{\text{Magnesia in original magma}}{\text{Magnesia in diluted magma}} = \text{dilution factor}$$

$$\frac{5.08}{3.11} = 1.6334$$

That is, unit volume of the magma must be increased by additions of outside material carrying no magnesia to a volume of 1.6334. Then to facilitate a comparison between the original and final magma, it is necessary that the same amount of magnesia shall be present in the final magma as in the original and shall be expressed in

the same figures. To do this, the composition of the final magma is multiplied by the dilution factor, as shown in Table V. The differ-

TABLE V

RELATIVE AMOUNTS OF COMPONENTS IN DILUTED MAGMA

	Final Composition	×	Dilut on Factor	=	Final Ratio
SiO_2	62.27	×	1.6334	=	101.89
Al_2O_3	14.28	×	1.6334	=	23.36
Fe_2O_3	2.08	×	1.6334	=	3.40
FeO	5.99	×	1.6334	=	9.77
CaO	5.32	×	1.6334	=	8.69
MgO	3.11	×	1.6334	=	5.08
K_2O	2.70	×	1.6334	=	4.41
Na_2O	3.52	×	1.6334	=	5.75
TiO_2	0.73	×	1.6334	=	1.19
Total	100.00		.....		163.34

ence between the final ratio and the original composition gives the amount of each component which has been added, and the sum of these additions is the total amount of material added to the magma. See Table VI.

TABLE VI

ADDITION OF 0.0 PARTS OF MGO

	Final Ratio	Original Composition	Amount Added	Composition of Average Blocks Added
SiO_2	101.89	53.28	48.41	76.40
Al_2O_3	23.36	17.46	5.90	9.30
Fe_2O_3	3.40	2.07	1.33	2.09
FeO	9.77	9.29	0.48	0.75
CaO	8.69	7.71	0.98	1.54
MgO	5.08	5.08	0.00	0.00
K_2O	4.41	1.69	2.72	4.28
Na_2O	5.75	2.69	3.06	4.82
TiO_2	1.19	0.73	0.46	0.72
Total	163.34	100.00	63.34	100.00

The magma has assimilated 63.34 per cent of its own volume of rock, so that

$$\frac{63.34 \times 100}{163.34} = 38.75 \text{ per cent of}$$

the present norite sheet is assimilated material. It is almost inconceivable that no magnesia has been added, since the lowest magnesian rock of the region, namely, the Mississagi quartzite, carries nearly .5 per cent of magnesia. The composition of this quartzite is given in Table VII.

TABLE VII*

	Per Cent		Per Cent
SiO_3	89.42	Na_2O	0.76
Al_2O_2	5.82	H_2O+	0.41
Fe_2O_2	0.30	H_2O-	0.04
FeO	0.97	TiO_2	0.17
CaO	0.15		
MgO	0.46	Total	100.15
K_2O	1.82		

* Mississagi quartzite. Analyst, G. W. Bain.

The results of calculations based upon the additions of various amounts of magnesia are given in Tables VIII, IX, and X. These tables show that if any magnesia is added, the total amount of material must increase correspondingly, and that the amount of material assimilated by sheets is quite large, approaching even their own volume in magnitude.

TABLE VIII

ADDITION OF 0.5 PARTS OF MgO

	Final Ratio	Additions	Composition of Added Blocks	Percentage of Additions in Sheet
SiO_2	111.59	58.31	73.57	109.4
Al_2O_3	25.60	8.14	10.28	46.6
Fe_2O_3	3.72	1.65	2.08	79.7
FeO	10.75	1.46	1.84	15.7
CaO	9.55	1.84	2.32	18.4
MgO	5.58	0.50	0.63	9.8
K_2O	4.85	3.16	3.99	186.9
Na_2O	6.31	3.62	4.57	134.5
TiO_2	1.31	0.58	0.73	79.5
Total	179.27	79.26	100.00	44.15

More recently Knight[1] collected samples across a linear section of the norite sheet in MacLennan Township on the eastern end of

[1] C. W. Knight, *Econ. Geol.*, Vol. XVIII, p. 593.

the range. One would expect the composition of the assimilated rocks, and even of the norite itself, to be slightly different from that at the southwestern end of the Sudbury basin. The differences,

TABLE IX

ADDITION OF 1.5 PARTS OF MgO

	Final Ratio	Additions	Composition of Added Blocks	Percentage of Additions in Sheet
SiO_2	131.76	77.48	69.43	130.1
Al_2O_3	30.20	13.74	12.31	77.9
Fe_2O_3	4.40	2.33	2.09	112.5
FeO	12.68	3.39	3.04	36.5
CaO	11.27	3.56	3.19	46.1
MgO	6.58	1.50	1.35	29.5
K_2O	5.71	4.02	3.60	23.8
Na_2O	7.45	4.76	4.26	177.0
TiO_2	1.55	0.82	0.73	112.2
Total	211.60	111.50	100.00	52.7

TABLE X

ADDITION OF 3 PARTS OF MgO

	Final Ratio	Additions	Composition of Added Blocks	Percentage of Additions in Sheets
SiO_2	162.00	108.72	68.00	204.0
Al_2O_3	37.05	19.59	12.23	112.1
Fe_2O_3	5.40	3.33	2.08	161.0
FeO	15.55	6.26	3.91	67.5
CaO	13.82	6.11	3.82	79.3
MgO	8.08	3.00	1.88	59.1
K_2O	7.01	5.32	3.32	314.5
Na_2O	9.14	6.45	4.03	240.0
TiO_2	1.90	1.17	0.73	160.2
Total	259.95	159.95	100.00	61.5

when worked out, are very slight, and the calculations are repeated merely to confirm the results previously obtained. The analyses cited by Knight[1] (Fig. 3) are given in Table XI.

The relative percentage change is determined as in the previous case, or

$$\text{Relative percentage change} = 100 \times \frac{(\text{Final composition} - \text{original composition})}{\text{Original composition}}$$

[1] *Op. cit.*

The results of the calculations are given in Table XIII, and show that alumina has been increased by the smallest amount. The factor of dilution is, therefore, obtained as follows:

$$\frac{\text{Alumina in original magma}}{\text{Alumina in diluted magma}} = \text{dilution factor}$$

$$\frac{23 \cdot 40}{13 \cdot 97} = 1.6750$$

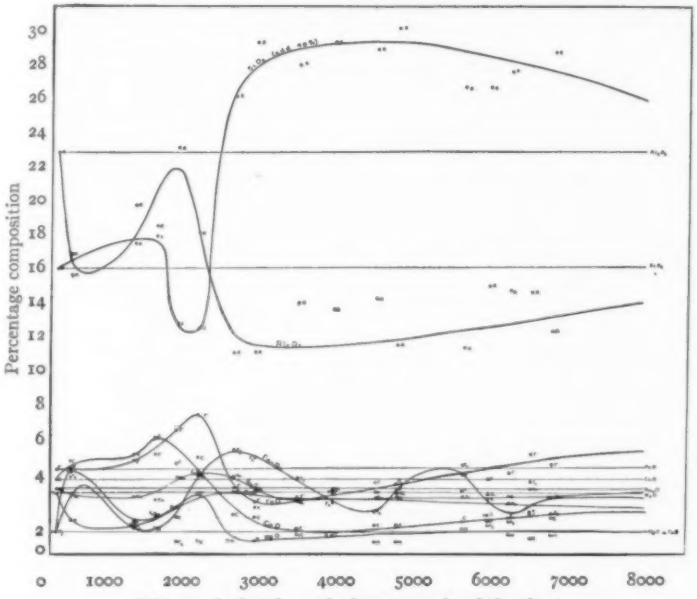

FIG. 3.—Graphic representation of Knight's analyses

The final ratios of the various constituents, on the hypothesis that no material has been removed from the sheet, are determined from this dilution factor and are expressed in Table XIV.

The amount of material added is given by the equation:

Final ratio − initial composition = amount added,

and the composition of the added material is obtained by converting the amounts into percentages, as shown in Table XV.

TABLE XI

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
SiO_2	56.21	57.10	57.74	58.19	53.14	52.86	66.05	69.08	67.80	69.10	68.76	69.84	66.58	66.50	67.40	64.04	68.50
Al_2O_3	22.85	15.93	19.93	18.67	23.17	18.34	11.46	11.55	14.32	13.95	14.55	11.90	11.79	15.26	15.01	14.89	12.57
Fe_2O_3	1.25	4.40	1.51	2.28	0.71	4.67	5.95	5.55	4.36	2.93	2.40	4.00	5.08	1.61	1.94	4.14	2.37
FeO	4.80	4.87	5.36	5.72	7.02	7.99	3.79	2.98	3.22	3.43	4.04	3.74	4.51	4.28	4.62	5.71	5.13
CaO	4.22	5.35	5.67	6.62	5.20	5.57	2.25	2.10	1.44	1.08	1.65	1.64	1.95	2.26	2.07	2.27	2.07
MgO	1.24	4.74	1.95	2.32	2.68	3.45	0.80	0.80	1.16	1.15	0.67	0.72	1.44	1.88	1.13	0.97	1.09
Na_2O	3.69	3.24	3.28	3.08	4.20	4.52	4.44	3.66	3.05	3.64	3.21	3.44	3.33	3.40	2.94	3.73	3.27
K_2O	3.45	1.92	1.67	1.48	2.14	0.79	3.60	2.66	3.14	3.58	3.58	3.27	3.66	3.16	3.37	2.43	3.30
H_2O	2.56	2.55	2.67	1.88	1.73	1.79	1.84	1.30	1.46	1.10	1.22	1.38	1.62	1.66	1.65	1.93	1.64
CO_2	.....	0.20	0.31	0.16	0.18	0.18	.....	0.24	0.24	0.21	Trace	0.26	0.25	0.18	0.17	Trace	0.27
Total	100.27	100.30	100.09	100.40	100.17	100.16	100.18	99.92	100.19	100.17	100.08	100.19	100.21	100.19	100.30	100.11	100.21

Analysts, W. K. McNeill and T. E. Rothwell.

These samples are, beginning with No. 1, 100, 300, 1,200 1,500, 1,800, 2,100, 2,600, 2,900, 3,500, 4,000, 4,600, 4,900, 5,800, 6,200, 6,500, 6,800, and 7,100 feet, respectively, southwest of the outer edge of the norite-micro-pegmatite.

Analyses previously published will be found in the *Report of the Royal Ontario Nickel Commission*, pp. 117–19.

TABLE XII

	1	2	3	4
SiO_2	56.21	57.52	66.30	+8.78
Al_2O_3	22.85	23.40	13.97	−9.43
Fe_2O_3	1.25	1.28	3.49	+2.21
FeO	4.80	4.91	4.96	+0.05
CaO	4.22	4.32	3.21	−1.11
MgO	1.24	1.27	1.69	+0.42
K_2O	3.45	3.53	3.32	−0.21
Na_2O	3.69	3.77	3.06	−0.71
Total	97.71	100.00	100.00	

1. Anticipated average content of principal constituents.

2. Anticipated average content of principal consituents corrected to 100 per cent.

3. Actual average content of principal constituents determined from the calculations.

4. Difference between actual and anticipated percentage.

TABLE XIII

	Final Composition Less Original Composition	÷	Original Composition	=	Relative Percentage Change
SiO_2	+8.78	÷	57.52	=	+ 15.22
Al_2O_3	−9.43	÷	23.40	=	− 40.30
Fe_2O_3	+2.21	÷	1.28	=	+173.50
FeO	+0.05	÷	4.91	=	+ 1.02
CaO	−1.11	÷	4.32	=	− 25.70
MgO	+0.42	÷	1.27	=	+ 33.00
K_2O	−0.21	÷	3.53	=	− 5.95
Na_2O	−0.71	÷	3.77	=	− 18.80
Total			100.00		

TABLE XIV

	Final Composition	×	Dilution Factor	=	Final Ratio
SiO_2	66.30	×	1.6750	=	111.05
Al_2O_3	13.97	×	1.6750	=	23.40
Fe_2O_3	3.49	×	1.6750	=	5.85
FeO	4.95	×	1.6750	=	8.30
CaO	3.21	×	1.6750	=	5.39
MgO	1.69	×	1.6750	=	2.83
K_2O	3.32	×	1.6750	=	5.56
Na_2O	3.06	×	1.6750	=	5.12
Total	100.00				167.50

SOURCE OF DISSOLVED MATERIAL

The Sudbury sheet is injected between the Sudbury series of pre-Huronian age and the Whitewater series of Animikean or very late Huronian time. At Lake Wanapitei, Quirke[1] found the norite in-

TABLE XV

	Final Ratio	–	Original Composition	=	Amount Added	Composition or Additions
SiO_2	111.05	–	57.52	=	55.53	79.30
Al_2O_3	23.40	–	23.40	=	0	0.00
Fe_2O_3	5.85	–	1.28	=	4.57	6.77
FeO	8.30	–	4.91	=	3.39	5.02
CaO	5.39	–	4.32	=	1.07	1.59
MgO	2.83	–	1.27	=	1.56	2.31
K_2O	5.56	–	3.53	=	2.03	3.01
Na_2O	5.12	–	3.77	=	1.35	2.00
Total	167.50		100.00		67.50	100.00

jected between the Laurentian granite and Keewatin schists to the east and the Trout Lake conglomerate to the west. One mile east of the contact between the norite sheet and the granite, Quirke found the base of the following succession of Huronian sediments:

Cobalt series
- Lorrain quartzite 5,000 feet (?)
- Gowganda formation 3,500 feet

Erosional and structural unconformity

Bruce series
- Serpent quartzite 800 feet
- Espanola greywacke 400 feet
- Bruce limestone 200–600 feet
- Bruce conglomerate 800 feet (?)
- Mississagi quartzite 5,000 feet (?)

The erosional unconformity between the Bruce series and the Cobalt series becomes so pronounced on the west end of the Sudbury Basin that the Gowganda formation and Lorrain quartzite overlie the Mississagi quartzite; only very small infolded basins of the four upper members of the Bruce series remain, and this is true to a lesser extent near Lake Wanapitei. The conglomeratic part of the Gowganda formation is frequently absent in many parts of the region, partly because of lack of deposition, and partly because of a small

[1] T. T. Quirke, *Sum. Rept. C. G. S., Pt. D*, 1921, p. 46.

disconformity between the conglomerate and quartzite members. Therefore, even after allowing for the absence of the members mentioned, a great thickness of sediments remains to be accounted for. These sediments are believed to have disappeared, in part at least, by solution in the norite magma and to have been the main source of the included blocks. Other sources of material are the Laurentian granite, the Keewatin volcanics, and the Sudbury schist, but in every possible case it is impossible to find a rock completely lacking in any oxide. The mass of material dissolved is probably greater, rather than less, than the mass of the original magma.

TABLE XVI

	5 Parts Al_2O_3	10 Parts Al_2O_3	20 Parts Al_2O_3	30 Parts Al_2O_3
SiO_2	74.78	72.61	70.45	69.41
Al_2O_3	4.83	7.19	9.48	10.62
Fe_2O_3	5.64	5.08	4.58	4.27
FeO	5.00	4.97	4.96	4.98
CaO	2.16	2.42	2.70	2.82
MgO	2.10	2.00	1.89	1.84
K_2O	3.12	3.18	3.22	3.25
Na_2O	2.37	2.55	2.72	2.81
Total	100.00	100.00	100.00	100.00

AMOUNT OF MATERIAL DISSOLVED

The amount of each oxide which would have to be added if a given amount of Al_2O_3 was added was determined as in the case of magnesia and is given in Table XVI.

These results were plotted (in full lines) on a silica base and gave straight-line curves (Fig. 4). The values determined in the first case, where magnesia was added in the least amount, were plotted in dotted lines. The curves for any oxide determined by the two series of analyses cross or are very close together when the silica in the added blocks approximates 68 per cent. The average block dropped into the magma is, therefore, believed to have carried approximately 68 per cent SiO_2, and the other constituents can be calculated from this known amount of SiO_2. See Table XVII.

For the magnesia calculations, the additions amount to at least one and one-half times the original mass of the magma solution, and

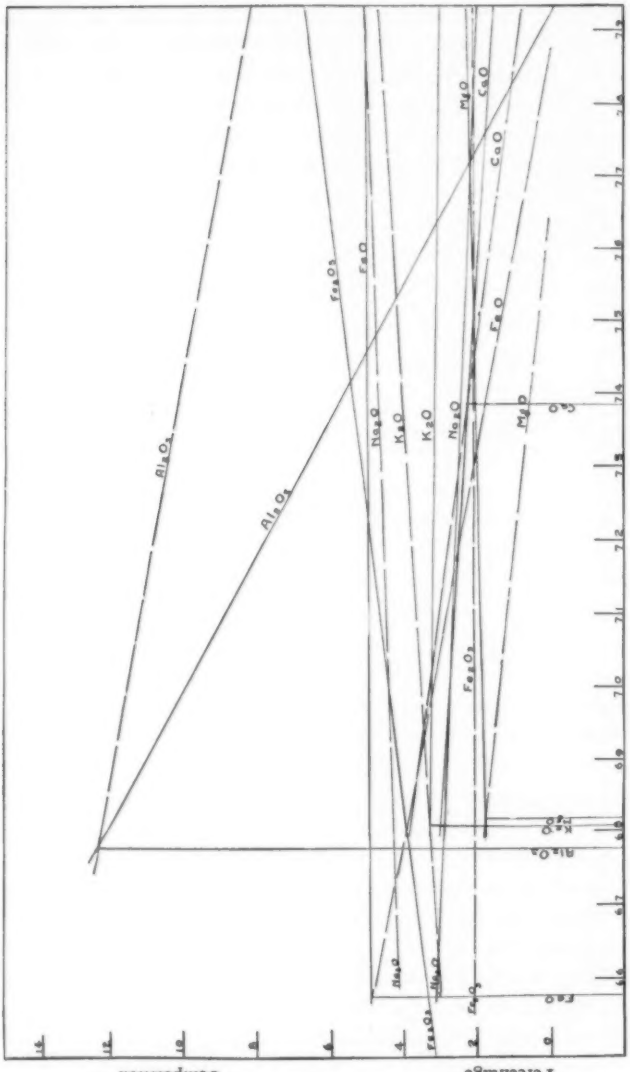

FIG. 4.—Curves showing variation in composition of included blocks. Curves deduced by Knight's analyses in full lines. Curves from compiled analyses in dotted lines.

for the alumina calculations slightly over three times the original volume of the magma must have been dissolved and reprecipitated on the base of the sheet.

CONCLUSIONS

The Sudbury norite sheet shows a variation curve from the base upwards which cannot be explained on the basis of simple magmatic differentiation, regardless of whether differentiation occurred by gravitational settling of crystals or by liquid immiscibility.

TABLE XVII

COMPOSITION OF BLOCKS

	MgO Calculations	Al_2O_3 Calculations
SiO_2	68.00	68.00
Al_2O_3	12.23	12.10+
Fe_2O_3	2.08	4.00
FeO	3.91	4.90+
CaO	3.82	3.00
MgO	1.88	1.80
K_2O	3.32	2.90
Na_2O	4.03	3.30
Total	99.27	100.00
TiO_2	0.73	.....

Curves representing the variation of the norite sheet across different sections vary due to variability in original dip of the sheet, thickness of the sheet, and the contact rock. The major feature, namely, the variance in a common direction from a simple differentiation curve, is characteristic.

The minimum assimilation which could have occurred is 63 per cent based upon analyses of rocks around the southwest end of the basin, and 67 per cent based upon rocks around the eastern end of the basin. The evidence seems to indicate that from 150 per cent to 300 per cent is nearer the correct figure.

The Mississagi quartzite, arkose, and iron formation seems to have been a possible source of the assimilated material.

MELILITE AND NEPHELITE BASALT IN HAWAII

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ABSTRACT

This paper lists the localities in Hawaii at which nephelite and melilite basalts have been obtained, and includes first records of melilite basalt from Niihau and of nephelite basalt from Kauai. General petrographic descriptions of the nephelite and melilite basalts from Kauai and Niihau are given. On each island, most of these lavas belong to the main eruptive complex. This controverts the hypothesis that the highly specialized magmas of the lava domes were developed during minor eruptive episodes which were initiated at subordinate centers during and after the close of the main volcanic period. On Kauai and Niihau, conditions of differentiation appear to have been more or less similar throughout the entire volcanic history, and probably like conditions prevailed on the other domes of the group. The reaction principle, outlined by Bowen, seems to afford the best explanation of the origin of the highly specialized rocks in the lava domes.

INTRODUCTION

In the writer's collection of the igneous rocks from the islands of Kauai and Niihau, Hawaii, made during two field seasons in 1921 and 1922, are a number of lavas containing nephelite and melilite. Since the publication of the report on the petrography and petrology of the igneous rocks must be delayed until the analyses of certain of the lavas are completed, it seems desirable to record the new localities at which melilite-bearing basalts have been found, to note the presence of nephelite basalt on Kauai (a variety not previously found on the island), and to discuss certain of the petrologic relations of these lavas.

PREVIOUS RECORDS OF NEPHELITE AND MELILITE BASALTS IN HAWAII

OAHU

Melilite basalt.—The history of the discovery of nephelite and melilite basalts in Hawaii has been given by Merrill[1] and Cross.[2]

[1] G. P. Merrill, "Nephelite-Melilite Basalt from Oahu, Hawaiian Islands," *Amer. Geologist*, Vol. XXV (1900), pp. 312–13.

[2] W. Cross, "Lavas of Hawaii and Their Relations," *U.S. Geol. Surv., Prof. Paper 88* (1915), pp. 20–21.

The first rock containing these two minerals was described by Wichman[1] in 1875 from rock ballast brought by a ship landing at Hamburg. The rock was said to have come from Oahu, but the exact locality was not known. Later studies were made by Cohen[2] and Stelzner,[3] both of whom confirmed the presence of nephelite and melilite. Wichman determined nephelite, olivine, hauynite, and melilite in the rock, but did not find augite; Rosenbusch,[4] in material supposedly from the same source, found neither hauynite nor melilite, but noted among the other constituents, nephelite and augite; Cohen identified nephelite, melilite, augite, olivine, and magnetite. Cohen thought it possible that lavas from more than one source had been examined by these various investigators.

Merrill[5] in 1900 published a note regarding a nephelite-melilite basalt from Moililii quarry, about halfway between Punch Bowl and Diamond Head, two cinder cones in the eastern suburbs of Honolulu. This rock was collected by Hitchcock, who believed that it came from the Rocky Hill craters in Moana Valley. Hitchcock also obtained melilite basalts from other localities near Honolulu: (1) at and near Rocky Hill, Moana Valley; (2) north edge of Kalihi Valley; (3) Gulick stream, west of Kamehameha School; (4) about ½ mile east of the Bishop Museum. Cross[6] published a description and analysis of the lava from Moililii quarry, mentioned above. The rock, which contains about 15 per cent of melilite and 25 per cent of nephelite, is classed as a casselose.

Möhle[7] also described a melilite-nephelite basalt, collected by the zoölogist, Schauinsland, from the vicinity of Honolulu. Since the exact locality was not recorded by Schauinsland, it is uncertain

[1] A. Wichman, "Nephelin Basalt von den Sandwich Inseln," *Neues Jahrb.* (1875), pp. 172–73.

[2] E. Cohen, "Über Laven von Hawaii, etc.," *ibid.*, Vol. II (1880), pp. 55–56.

[3] A. Stelzner, "Vorlaufige Mittheilungen über Melilithbasalt," *ibid.*, Vol. I (1882), p. 229.

[4] H. Rosenbusch, *Mikroskopische Physiographie der Massigen Gesteine* (Stuttgart, 1875), p. 510.

[5] *Loc. cit.*

[6] *Op. cit.*, pp. 20–22.

[7] F. Möhle, "Beitrag zur Petrographie der Sandwich- und Samoa-Inseln," *Neues Jahrb.*, Beilage Band XV (1902), p. 83.

whether this lava is the same as either of the rocks described by Wichman or by Cross. Powers[1] gave additional localities on Oahu at which he obtained melilite-bearing basalts:

East Oahu
Maumae Cone, tuff and scoria, nephelite-melilite basalt
Ulupau Crater, tuff cone, melilite-nephelite basalt
Puu Hawaii Loa, tuff cone, melilite-nephelite basalt

These flows apparently are associated with local eruptive centers, and are of comparatively recent date.

Nephelite basalt.—Cross[2] briefly noted the general characters of several lavas in the Hitchcock collection which he classed as nephelite basalts, "although this name unduly emphasizes a very subordinate constituent." While little is known of the field relations of these lavas, they are believed to be of Recent origin. The localities at which Cross obtained these rocks are: (1) Punch Bowl, near Honolulu, probably from a dike; (2) Kapupai, one of the Laeloa craters; (3) one of the salt craters; (4) a dike in the Pali road, to the east of and about 750 feet below the pass (this rock probably is a limburgite). "Allied rocks which may be called nephelite basanite occur at Diamond Head [dike?] and at Kapolei, a crater of the Laeloa group."

Powers[3] obtained nephelite basalts from Puu Papailai, a lava cone, and from Puu Makakilo, a scoria and lava cone, on west Oahu. Möhle[4] noted a nephelite basalt from Oahu in the Schauinsland collection.

MAUI

Möhle[5] described a melilite-nephelite basalt from near Lahaina, west Maui.

From two localities on east Maui: (1) White Hill (elevation, 9,780 feet) on the extreme southwestern angle of the depression at the summit of Haleakala, and (2) a ravine west of Vieira's ranch on the east slope of Haleakala, Cross[6] collected nephelite-bearing lavas,

[1] S. Powers, "Notes on Hawaiian Petrology," *Amer. Jour. Sci.*, Vol. L (1920), p. 273.

[2] *Op. cit.*, p. 23.

[3] *Loc. cit.*

[4] *Op. cit.*, pp. 83, 84.

[5] *Op. cit.*, pp. 69–70.

[6] *Op. cit.*, pp. 30–32.

of which he later published descriptions and analyses. These rocks are predominantly soda rich, plagioclasic lavas with some orthoclase, nepheline, olivine, and other mafic silicates. Cross classified them as essexitic andesites or trachyandesites (trachydolerites of the Rosenbusch system); the White Hill rock is an akerose; that from the east slope of Haleakala an essexose-akerose.

MOLOKAI

Möhle[1] records a nephelite basantoid in the Schauinsland collection from Kalae, a locality in the interior of east Molokai, north of Kaunakakai on the road to Kalaupapa.

HAWAII

The recent studies by Washington of the igneous rocks of the various eruptive centers on the island of Hawaii have not brought to light nephelite- or melilite-bearing lavas, nor have any been found by previous investigators. Washington[2] states that "apart from the trachytes, whose relations to the other lavas we do not know, there has been no splitting off of alkalic sub-magmas with nephelite or acmite." Except for the work of Noble and Clark on the geology of Mauna Loa and for investigations at Kilauea, geological research on Hawaii has been entirely of reconnaissance nature, and the igneous rocks have not been systematically collected. The possibility of finding rare rock types is by no means exhausted, since Washington[3] himself admits that "at Kohala we knew only the flows that appear at the surface, especially on the west slope; the earlier flows that may be exposed in the steep walls of the deep erosion ravines on the northeast side . . . . have not yet been studied." In general, equally little is known of the other volcanoes of the island. It therefore seems premature to conclude that no nephelite or melilite rocks are present.

KAUAI

Melilite basalt.—Cross[4] described a melilite-nephelite basalt from ledges near the landing for interisland boats on the west side of

[1] *Op. cit.*, p. 78.

[2] H. S. Washington, "Petrology of the Hawaiian Islands: Kilauea and General Petrology," *Amer. Jour. Sci.*, Vol. VI (1923), pp. 359–60.

[3] *Op. cit.*, p. 358.

[4] *Op. cit.*, pp. 16–17.

Kilauea Bay, northern Kauai. Cross considered that the flow, which is overlaid by tuffs and breccias of a nearby cinder cone of probably Recent origin, was erupted from the same center, though this relationship was not actually established. Powers[1] also expressed the same opinion after an examination of the locality. The present writer is unable to agree with these findings. As Cross observed, near Kilauea Bay, recent tuffs overlie the melilite basalt flow, but, $\frac{1}{8}$ mile from the coast, an apparent continuation of the same flow underlies deeply weathered lavas which form the surface of the lowland of northern Kauai. These lavas, including the flow in question, are part of the series composing the main mass of the Kauai dome, and were erupted long before the cinder cone near Kilauea Bay. The lowland referred to is a portion of a marine abrasion platform which was eroded deep into the Kauai dome and later was uplifted so that its inner margin now stands at least 500 feet above the present sea-level. Wherever observed, the melilite-basalt flow appears to be conformable with the underlying lavas; in no place does it rest upon lateritic soil formed by the weathering of the rocks below, as is the case in other sections of Kauai where lavas of the latest volcanic episode have been extruded upon the erosion surface. The top of the flow underlying the Kilauea melilite basalt is weathered to the degree prevalent in the upper parts of buried lavas of the principal eruptive period. The evidence obtained by the writer therefore indicates that the flow at Kilauea Bay belongs to the series composing the main mass of the Kauai dome, and that this flow was erupted below sea-level. From the amount of fluviatile and marine abrasion to which the island has been subjected, the principal volcanic period probably ceased in the late Tertiary; the flow in question was erupted long before the sealing of the principal vent, since about 5,000 feet of lava were subsequently erupted.

The writer found six other flows of melilite basalt on Kauai, all but one of which apparently belong to the principal eruptive series. The single exception is a lava of the latest volcanic episode, exposed along the shoreline at and near the Spouting Horn, west of Koloa, southern Kauai.

Microscopic petrography.—The melilite lavas are dark gray to

[1] *Loc. cit.*

black, dense rocks in which abundant, small, generally very brilliant, dark-green olivine phenocrysts are visible. Small vesicles are fairly abundant, and larger, irregularly shaped gas pores are scattered through the rocks. Partial or complete filling of the vesicles by zeolitic aggregates, calcite, or opal is common.

Examination of the thin sections shows the lavas to be composed essentially of augite, olivine, melilite, nephelite, and magnetite in varying amounts. Biotite and apatite are the only accessories. According to the relative abundance of nephelite and melilite, the rocks vary from nephelite-melilite basalts to melilite-nephelite basalts. Pleochroic, violet, or brownish-violet augite, the dominant mineral in all of the sections, is present in anhedral grains, which are occasionally of phenocrystic proportions. Olivine is the chief phenocrystic mineral. The largest individuals measure 0.8 millimeter in length and 0.3 millimeter in thickness. Smaller grains compose varying proportions of the groundmass. Inclusions of small magnetite grains are abundant in most of the phenocrysts. The mineral, where fresh, is colorless. Oxidation has produced narrow, brownish or reddish, oxidized rims in some of the sections; serpentine is a less common alteration product. Many of the phenocrysts have been strongly resorbed.

The melilite individuals are frequently microporphyritic; in other cases, the grains are of the average size of the groundmass. The largest tablets rarely exceed 1 millimeter in length. Euhedral individuals are present, but more often the basal planes are obscured by the penetration of the other constituents, principally by augite, nephelite, and magnetite. When the basal planes are poorly developed, the crystals assume the characteristic, rudely biconcave form. The mineral is colorless, and, in most of the sections, is comparatively fresh. "Peg structure," in rudimentary or well-developed form, is present in a few of the sections. The polarization colors are usually dark blue to purple, less commonly light blue, milky white, or yellowish. Lighter polarization colors either along the borders or in the cores of some of the tablets indicate variations in the refractive index of the different parts. Melilite generally composes from 10 to 20 per cent of the rocks.

Magnetite is abundant in only two of the sections examined. The

grains are generally anhedral, and not infrequently are microporphyritic. The skeleton rods and crystals, so characteristic of the olivine basalts of Kauai, are rare. Cross[1] believes that all of the magnetite of the nephelite and melilite basalts is titaniferous; the analysis of magnetite powder from a melilite basalt from Oahu gave 13.4 per cent TiO_2. None of the decomposition products of titaniferous magnetite were found by Cross in the melilite basalts of Oahu nor by the writer in similar rocks from Kauai.

Nephelite is present in small, euhedral, subhedral, or anhedral grains, which compose not more than 25 per cent of the volume of the lavas. Some of the nephelite shows a slight amount of alteration along the cleavage lines.

Biotite and apatite are the only accessories, and are present in all of the sections examined. The biotite grains are irregular in outline, and rarely exceed 0.3 millimeter in their maximum dimension. The pleochroism varies from deep reddish-brown through pale brown to light golden-yellow. Small acicular needles and basal sections of apatite are abundant.

Zeolites, calcite, and less commonly opal are present as fillings of the vesicles.

The lavas are holocrystalline, except for occasional globules of isotropic or partially devitrified glass.

Cross[2] gives an analysis of the rock from Kilauea Bay, which is classed as a uvaldose.

The other localities on Kauai at which the writer collected melilite-bearing lavas are: *Nephelite-melilite basalt:* (1) about 2 miles west of Kilauea plantation, northern Kauai, along an old road to a former boat landing (elevation 150 feet); (2) near the bed of Hanapepe River, southern Kauai, $\frac{1}{8}$ mile upstream from the ditch tender's house (elevation 500 feet); (3) 1 mile south of Puu Ka Ele reservoir near Kilauea plantation, northern Kauai (elevation 550 feet); (4) near the bed of the north fork of the Wailua River, $\frac{1}{2}$ mile west of the Kauai Electric Power Line trail, eastern Kauai (elevation 500 feet); (5) along the shoreline at and near the Spouting Horn, west of Koloa, southern Kauai. This lava, which apparently came

[1] *Op. cit.*, p. 22.

[2] *Op. cit.*, p. 17.

from a vent near the inner margin of the southern lowland, is the only melilite basalt which can be definitely assigned to the late, local volcanic episodes. *Melilite-nephelite basalt:* (1) about 2 miles from the mouth of Koaie Canyon, western Kauai (elevation 1,520 feet); (2) along the trail to Waialeale, 4 miles east of Kohaluamanu, central Kauai (elevation 4,060 feet). This lava is unusually rich in magnetite; melilite and nephelite are minor constituents.

Nephelite basalt.—At eight localities on Kauai, the writer found nephelite basalt, a petrographic variety not previously reported from the island. The rocks are grayish black, generally minutely vesicular, dense, aphanitic types, in which small olivine phenocrysts are abundant. The flows from which the specimens were collected belong to the lower third of the principal eruptive series. No nephelite basalts were found which could be definitely associated with vents of the late eruptive episodes.

Microscopic petrography.—Abundant, fresh or partially altered, euhedral, subhedral, or anhedral olivine phenocrysts are imbedded in a medium- or fine-grained groundmass, composed of augite, olivine, magnetite, nephelite, and subordinate amounts of apatite and biotite. The olivine phenocrysts generally do not measure more than 1 millimeter in length and 0.3 millimeter in thickness. Where fresh, the mineral is colorless. Magnetite inclusions are common, and, in certain of the sections, collars of magnetite grains, intergrown with the material of the outer zone of the olivines, more or less completely surround the phenocrysts. Narrow, brownish, limonitic rims are present in most of the individuals, and pale, bluish-green serpentine has developed occasionally along the cleavage cracks. Magnetite euhedrons and subhedrons are abundant in the groundmass; microphenocrystic anhedrons are not uncommon. The nephelite individuals are subhedral or anhedral in outline. Nephelite apparently composes from 5 to 20 per cent of the volume of the lavas. Minute, irregular plates of biotite and abundant prismatic or basal sections of apatite are present.

Zeolites, among which natrolite and analcite were recognized, fill many of the vesicles.

The localities at which nephelite basalt was obtained on Kauai are: (1) $\frac{3}{4}$ mile north of Nawiliwili Landing, eastern Kauai (elevation

100 feet); (2) Anahola Canyon, near the bend southeast of Puu Konanae (elevation 200 feet); (3) 1 mile west of Kilauea plantation, northern Kauai (elevation 150 feet); exposures along the Wailua Ditch, 1.5 miles west of the Kauai Electric Power Line trail, eastern Kauai (elevation 650 feet); (5) 1.5 miles east of Anahola reservoir, northeastern Kauai (elevation 600 feet); (6) Lihue ditch, 4 miles west of Lihue, eastern Kauai (elevation 700 feet); (7) $\frac{1}{4}$ mile northeast of Grove Farm reservoir, eastern Kauai (elevation 600 feet); (8) along road in Olokele Canyon (elevation 1,550 feet).

NIIHAU

The only melilite basalt recorded from Niihau was collected by the writer from a flow of the main eruptive series about $\frac{3}{4}$ mile above the mouth of Keanauhi Canyon, on the northern side of the basaltic highland. The rock is a medium-gray aphanite, containing a few rounded vesicles, rarely exceeding 2 millimeters in diameter. Slightly more coarsely granular, more or less parallel, lighter gray streaks give to the rock a rude flow structure.

The lava is composed of unaltered, euhedral or subhedral olivine and small magnetite phenocrysts which are set in a comparatively fine-grained groundmass, composed of augite, magnetite, and lesser amounts of olivine, melilite, and nephelite. Apatite and biotite are accessory minerals. The largest of the olivine individuals measure 0.8 millimeter in length and 0.3 millimeter in thickness. Small olivine anhedrons form a part of the groundmass. Occasional streaks of bluish-green serpentine are the only evidences of alteration of the olivines. Augite, the principal constituent of the rock, is present in strongly pleochroic, deep brownish-violet anhedrons.

The microporphyritic tablets of melilite rarely exceed 0.6 millimeter in length and 0.2 millimeter in thickness. The basal planes generally are obscured by the penetration of augite, nephelite, and magnetite. "Peg structure" was not observed. Nephelite is present in small subhedral grains as an important constituent of the groundmass. The percentage of magnetite is unusually high for the melilite basalts; a few of the individuals are microphenocrystic. Abundant, acicular prisms and basal sections of apatite and a few irregular grains of deep chocolate-brown biotite are present.

Practically all of the vesicles are more or less completely filled with zeolites, principally natrolite and analcite.

The rock is a magnetite-rich melilite-nephelite basalt; in its high magnetite content, it resembles the melilite-nephelite basalt from the Waialeale trail on Kauai (No. 5). No melilite basalts were found on Niihau which could be associated with the centers of recent eruptivity.

RELATIONS OF THE MELILITE AND NEPHELITE BASALTS

The discovery of nephelite basalt on Kauai and of new occurrences of melilite basalt on Kauai and Niihau makes desirable a brief consideration of the relations and the genesis of these and other related, highly differentiated lavas. That these rocks are widespread in the lava domes of the world, though of limited local development, may be seen from a survey of Daly's list[1] of the islands in the Pacific Ocean composed essentially of volcanic rocks. This list shows that "alkaline" and related rocks have been found on thirty-five islands representing thirteen of the major groups and on two isolated islands. As noted by Daly, "in thirty of the islands, the alkaline rocks are associated with feldspar basalt or its equivalent gabbro."

The representation of "alkaline" and associated types in Hawaii, including records of later date than that of Daly's paper, are:

Trachydoleritic Basalt	Trachyte	Oligoclase Rocks
Haleakala, east Maui	Hualalai, Hawaii	Kohala, Hawaii
Mauna Kea, Hawaii	West Maui	Kauai (oligoclase gabbro)
	Laysan	Molokai
Trachyandesite	**Nephelite Basalt**	**Nephelite Basanite**
Haleakala, east Maui	East Oahu	East Molokai
	West Oahu	
	Kauai	
Melilite Basalt	**Limburgite**	
West Maui	Oahu (?)	
East Oahu	Kauai (?)	
West Oahu		
Kauai		
Niihau		

[1] R. A. Daly, "Petrography of the Pacific Islands," *Bull. Geol. Soc. Amer.*, Vol. XXVII (1916), pp. 330–40.

The fact that alkaline rocks have not been reported from other groups may be attributed to the slight amount of geological work which has been done in the Pacific Islands and not to the absence of these types. Detailed investigations will doubtless greatly increase the number of localities at which highly specialized lavas may be obtained. As Daly[1] has stated, 370 of the Pacific Islands have been definitely described as volcanic, but it is probable that the whole number of them exceeds 600. "Of those only about 180 have furnished any information regarding the nature of their constituent rocks. Not a single island has yet been studied and mapped in the detail suited to the needs of petrology."

So far as Kauai and Niihau are concerned, the nephelite and melilite basalts with but one certain exception were obtained from flows at various horizons within the main mass of the dome; one flow definitely belongs to the latest, probably Recent lavas of the island. The development of these highly differentiated lavas during the principal eruptive period throws serious question on certain conclusions set forth by Cross and Powers regarding the time of appearance of such magmas in the history of the building of the Hawaiian lava domes. Cross[2] states that "the more salic and femic lava types are as a rule the products of these recent and local eruptions," though he is not

> in a position to assert either that they are restricted to such outbursts or that all lavas of the eruptions are of highly differentiated character. But that such is the general rule is well established. . . . . If we assume that the initial magma at each center of eruption was of basaltic charcter, ... it seems that during the more active period of each volcano differentiation was seldom if ever able to produce partial magmas of extremely salic or femic character. . . . . At any rate lavas of extreme composition are not known in the main mass of any volcano.

Cross concludes that "in the long period of parasitic or subsidiary eruptions conditions were favorable for extreme differentiation. This may be due to localization of smaller magma chambers or to lengthened periods of quiet." Powers[3] follows Cross in stating that "toward the close of the evolution of the volcanic edifice another change appears to take place,—the appearance of the more unusual rock

[1] *Op. cit.*, p. 326. [2] *Op. cit.*, pp. 91–93. [3] *Op. cit.*, p. 280.

types." Powers believes that the volcanoes late in their history lost connection with the primal magma from which they were fed, after which event differentiation proceeded in the isolated magma chambers of the larger volcanoes. "The extreme products of Hawaiian vulcanism, nephelite basalt and trachyte, may appear either at the close of the main vulcanism or in a later phase after extensive erosion."

The discovery by the present writer of highly differentiated rocks at various horizons within the principal eruptive complexes of Kauai and Niihau proves that ultra-femic magmas were generated during the main eruptive period, as well as during the later, intermittent, local eruptive episodes, quite the reverse of the opinion expressed by Cross and Powers. Highly salic differentiates, like trachyte, have not been found on either Kauai or Niihau, but may yet be reported. Andesite and olivine basalt were the dominant lavas erupted both during the principal volcanic period and during the minor eruptive episodes. In all cases where the sequence is visible, the nephelite and melilite rocks are underlaid and overlaid by normal andesitic or basaltic lavas, but, of course, the eruptions immediately preceding and following those of the highly differentiated magmas are not necessarily represented by the flows above and below. Were it possible to trace the exact eruptive sequence, systematic variations might be found from the ordinary andesitic and basaltic types to the femic pole and to petrographic types more salic in composition than any yet discovered. It is possible that this differentiation was accomplished during intervals of relative quiescence, when movements within the magma column were reduced to a minimum, and, as a result, a more or less perfect density stratification of the magma had taken place. When rejuvenation of activity subsequently developed, the following sequence of eruptions may have taken place: (1) salic phases, represented by the most salic andesites or by undiscovered rocks such as trachyte; (2) andesite and highly plagioclasic olivine basalt; (3) normal olivine basalt (the principal type); and (4) ultra-femic magmas. Of the latter, ultra-femic olivine basalt, picrite basalt, and picrite are the dominant types; the nephelite and melilite basalts are less common. The mechanism and the products of differentiation at the varous eruptive centers on Kauai and Nii-

hau appear to have been similar during both the principal eruptive period, when the main mass of the dome was constructed, and during the local, intermittent, and relatively short-lived volcanic episodes which continued long after the principal vent had been sealed. Further investigations of the other principal eruptive centers in Hawaii will probably confirm the data obtained on Kauai and Niihau—namely, that the highly specialized lavas, such as the nephelite and melilite basalts and trachytes, are associated with the normal lavas throughout the entire eruptive sequence.

GENESIS OF THE NEPHELITE AND MELILITE LAVAS

Of the various explanations of the genesis of the "alkaline" and related rocks of the lava domes of the world, the operation of the reaction principle, as outlined by Bowen, seems most satisfactory. Bowen[1] considers that most of these lavas have been formed by the differentiation (crystal accumulation) taking place in an alkali-rich magma. The intimate association of melilite and nephelite in nature indicates that the former mineral is the normal "cafemic constituent of nephelite-bearing rocks." In his latest paper dealing with the genesis of melilite, the same writer[2] states that some melilite is probably produced by

> the addition of lime to ordinary basalts, but when so formed one would expect it to be found in the deep-seated rocks as commonly as in the effusive or dike rocks. The fact that melilite is practically absent from the deep-seated rocks suggests the dominance of the other method of production, namely, the interaction of nephelite and pyroxene, which requires rapid cooling accompanying eruption in order to prevent its reversal at low temperatures.

From an examination of a melilite-nephelite basalt from Oahu, Bowen concludes that the irregular interlocking of augite with the other mineral constituents indicates that melilite was formed by the attack of the alkaline residual liquid upon augite, though he notes that melilite does not occur in the typical "reaction-rim form." The present writer observed similar relations between the augite

[1] N. L. Bowen, "Genetic Features of the Alnoitic Rocks at Isle Cadieux, Quebec," *Amer. Jour. Sci.*, Vol. III (1922), p. 28.

[2] "The Genesis of Melilite," *Jour. Wash. Acad. Sci.*, Vol. XIII (1923), pp. 1–4.

and other minerals in the sections of melilite basalt from Kauai and Niihau.

That all "alkaline" and related rocks are generated by the process of differentiation set forth by Bowen does not follow. Many alkaline magmas probably have been developed by the solution of sedimentary material through which they have passed after the manner advocated by Daly.

A NEW TYPE OF SILURIAN WORM

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ABSTRACT

An extraordinary type of fossil, manifestly related to *Serpulites* and *Conularia*, is described from the Silurian strata near Chicago. It is clearly a new genus and species and is given the name *Lecthaylus gregarius*. It is associated with a species of *Monograptus*, a genus which is poorly represented in the American Silurian faunas, but which abounds in Europe.

Ruedemann[1] has pointed out the characteristics of certain more or less elongate, tubular, chitinous fossils which are referred to the genus *Serpulites*. The objects are attached by means of adhesion disks, and in one species (*S. gracilis*), chitinous rods or setae are present back of the aperture of the tube, which suggest their relationship with the *Chaetopodous* worms. The same author points out the similarity of these chitinous tubes of *Serpulites* with the chitinous tests of *Conularia*. Furthermore, it has been shown that in some cases at least, *Conularia* is attached by adhesion disks similar to those in *Serpulites*. Such attached examples have been beautifully shown by Ruedemann,[2] and an excellent English specimen has been illustrated by Miss Slater.[3] From these observations it seems to be not improbable that *Serpulites* and *Conularia* are the fossil remains of more or less closely related segmented worms of some sort.

Recently another type of these chitinous, tubular fossils was discovered in the Silurian strata near Chicago. It is clearly related to those previously known, but possesses characters indicative of a distinct generic type. The specimens have been collected at a single locality from the rock excavated during the construction of the Calumet feeder for the Chicago drainage canal, just southwest of Blue Island. They occur in a bed of fine-grained, grayish-brown, thinly laminated rock which is largely dolomitic, but which on

[1] *N. Y. State Mus. Bull. No. 189* (1916), pp. 83–89.

[2] *Fifteenth Ann. Rep. N.Y. State Geol.* (1897), pp. 701–28.

[3] Monograph, *British Conularia*, Pa. Soc. (1907), Pl. 2, Fig. 1.

solution leaves a residue, equal to nearly one-half its mass, of fine gray mud. Some of the laminae appear as nearly black lines produced by the presence of carbonaceous material. This brownish, more or less shaly bed is apparently interstratified with the yellowish dolomite which prevails in the region, but its thickness has not been determined because it is known only from the rock dumps by the side of the canal. Judging from the material observed, however, this bed cannot exceed two feet in thickness, and it may be only half that. The peculiar fossils under consideration are apparently restricted to a thin layer of not more than one or two inches within this thicker, shaly bed, but where they do occur they are represented by innumerable examples. These "worm tubes," if they be such, are associated with a species of *Monograptus* which has been identified as *M. vomerius* (Nich.), described from the Wenlock of England, and said to be distributed throughout that formation. In the Blue Island locality the specimens of *Monograptus* are present in the inch or two of sediments where the "worm tubes" occur, but they are also distributed more generally throughout the whole brown layer. Other fossils which occur less commonly in the same bed are two or more species of dendroid graptolites, represented by comparatively few specimens, and two species of inarticulate brachiopods, represented by one example each in the collection which has been studied.

The geographic extent of the peculiar brown, shaly bed containing this assemblage of fossils is not known. It occurs upon the spoils dump of the canal for only a short distance, where it must have constituted the lowermost rock excavated. With the gentle regional dip to the east, it is doubtless carried beneath the bed of the canal in that direction, and west of where the material is now exhibited it must have been present above the bottom of the canal, so that the material there excavated is now covered in the dump with rock which lay beneath it and was taken out later. The geological position of the bed is within the confines of the Racine dolomite division of the Silurian, as that term is used by Bassler.[1]

DESCRIPTION OF NEW GENUS AND SPECIES

Lecthaylus gregarius n.gen. and sp. (Fig. 1).—The individuals of this species were flask-shaped bodies attaining a total length of from

[1] *U.S. Nat. Mus. Bull. No. 92* (1915), Vol. II, Pl. 3.

70 to 75 millimeters or more. In the flattened condition as they occur in the rock, the greatest width is about 12 millimeters at a distance of from 15 to 18 millimeters from the base. Above the line of greatest width the body tapers gradually to a little less than 3 millimeters, beyond which point the sides become nearly parallel

FIG. 1.—*Lecthaylus gregarius*. A colonial group in which portions of no less than ten individuals may be recognized.

through some 20 millimeters of the distal portion. When reconstructed from the crushed condition, each one of the individuals would possess an expanded, bulblike proximal portion, tapering out into an elongate, slender, tubular portion distally. These flask-shaped bodies are attached at the base of the broader, bulblike portion, in clusters or perhaps singly in some cases. In no example observed is the actual surface of attachment clearly exhibited, but there seems

to be little or no narrowing of the body toward what must have been the disklike base. The number of individuals in the groups or clusters is variable; in some of the groups observed there may be as many as ten or more individuals. The bulblike proximal portions are in close proximity, and the slender, tubelike distal portions seem to have been more or less flexible during life. In its proximal, broader portion, the surface is marked by distinct transverse lines about 0.2 millimeter apart near the base, becoming more widely spaced above, where some are 0.5 to 1 millimeter apart a short distance above the line of greatest width. As the sides of the body taper distally, the transverse markings disappear, or at least become nearly obscured by conspicuous, longitudinal, more or less irregular, wrinkle-like markings, which are more or less wavy and become indistinct toward the distal extremities, where they merge into a more or less irregularly roughened surface. Upon some examples the markings of the tubular, distal portion seem to exhibit a somewhat regular succession of elongate, diamond-shaped areas. In some of the individuals one or two of the longitudinal markings of the distal portion of the body, as seen upon one exposed surface, continue proximally across the broader, transversely marked portion, suggesting that this part of the body may have been divided longitudinally into four or more sections. There is no uniformity in this last feature, however, and the longitudinal markings may be fractures produced by the flattening of the bodies as they became buried in the inclosing sediments.

Among the specimens which have been observed considerable variation is exhibited, although many of the specimens which have been collected are more or less fragmentary, so that the dimensions and proportions are not determinable. In one example the broader, proximal, transversely marked portion of the body attains a length of at least 60 millimeters, but the narrower, distal portion of the specimen is only partially preserved, so that it is not possible to determine whether the relative proportions between the two parts remain the same.

In the collection there are one or two groups of individuals which seem to be attached to another example of the same animal. In such cases the younger, attached individuals are much smaller than the host upon which they are growing, and they stand out at nearly

right angles in all directions from the tube to which they are attached. None of these individuals are really well preserved, which may be due to the fact that the tube walls are thinner and more delicate in the younger examples.

The material of which these fossils are constituted is jet black in color and apparently carbonaceous, and they stand out in strong contrast upon the surfaces of the rock which contains them. The appearance of this material is not unlike that of some of the examples of *Serpulites* that have been described, and examples of *Conularia* in some conditions of preservation seem to be entirely similar in character.

THE EXTRACTION OF FOSSILS FROM REFRACTORY ROCKS

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ABSTRACT

The new process described makes use of the oxyacetylene flame. The surface of the matrix rock is heated with this to a very high temperature, and before the heat has time to penetrate to the fossil, water is applied for sudden cooling. The process makes possible the obtaining of fossils from rocks so hard and tough that it has been impossible to secure them otherwise.

In connection with a study of the fossils of California Eocene deposits a process has been devised for the successful extraction of specimens from rocks of excessive hardness and toughness. The only apparatus necessary, other than that ordinarily found in the paleontologist's kit, is a small oxyacetylene welding outfit such as almost every commercial garage is now equipped with. Tanks holding 50 or 100 cubic feet each of compressed oxygen and acetylene can be obtained now on short notice in practically any part of the country. Each tank must be equipped with a pressure reduction valve and gauge. The best torch for small and medium-sized work is that known as a "jeweler's model," which comes supplied with three tips bored to give flames varying from a "needle point" to one of about three times that volume.

In practice the flame is held on the matrix rock to be removed from the fossil. A few moments only will suffice to melt the surface to a brilliant white, when water is suddenly dropped on. So quickly is the heating effected that even in very thin layers of rock the heat does not have sufficient time to penetrate to and injure the specimen. The sudden and violent generation of steam from the water usually causes decomposition of the matrix, and it breaks away from the fossil with unbelievable ease.

The process was developed in the course of a study made of the paleontology of the Tejon Eocene at its type locality. There the matrix is a very hard, fine-grained sandstone with the fossils per-

fectly preserved. The character was such that minute forms of mollusks could not be extracted at all, and most of the others were badly disfigured by the use of the ordinary hammer and chisels. But the oxyacetylene flame enabled me to secure a large and varied fauna, strictly comparable with other classical Eocene collecting-localities.

Since then occasion has arisen to test the flame process thoroughly in the preparation of fossils from many kinds of rocks, and it has proved to be so useful that it deserves to rank along with the microscope as an aid to the paleontologist. Hinges of bivalves so completely cemented in hard rock that exposition would otherwise be utterly impossible can be perfectly cleaned in a few moments with the oxyacetylene torch. A little practice, only, is required for the operator to learn the correct amount of heating so that the operation need not be repeated.

The process was found to work equally well and with comparatively great rapidity on ammonites preserved in hard limestones. The most minute umbilical coils were exposed, in many cases with not more than five seconds of heating and two drops of water. The structures on these particular fossils could never have been uncovered by the use of ordinary tools, such as awls or chisels.

Again, it was found that Paleozoic brachyopods, preserved in a limestone to which they adhered so firmly they could not be detached by mechanical means at all, came out as clean and perfect as any student could desire.

The writer recalls that during his early days in paleontology a month was spent chiseling the skull of a Miocene mammal out of a rock which was not exceptionally tough or hard. By way of comparison, a similar task on exactly the same character of matrix was accomplished in an hour and a half. And whereas the first was broken many times and had to be glued together, scarcely a fragment was detached from the last.

It was also found that when bones or other specimens have a thin coating of mineral deposit, such as iron oxide, it is often necessary to chisel and scrape every particle of surface to get thoroughly cleaned material. In this process the minute surface structure of the fossil is usually completely destroyed. But with the flame the

same deposit came off in large flakes, leaving perfectly prepared specimens.

It is believed the apparatus has been given sufficient trial to warrant its being recommended unqualifiedly for any laboratory where fossils are prepared for study. Perhaps it may be surmised that other methods of heating would be equally effective, but after repeated trials of various gas burners, gasoline torches, etc., it was found that the rate of heating was so slow they were all practically useless. It is necessary that the heating on the surface be rapid and excessive, so as to prevent injury to the specimens.

As accessories to the oxyacetylene outfit a few items may be mentioned, since they have been found to be all that seemed to be required. The ordinary rubber bulb "ear syringe" makes an ideal water container. Dissecting-needles suffice to pick away the broken pieces of rock. An exceedingly useful instrument for chipping away pieces of rock has been made from a small pair of pliers having long, round "jaws." About one-eighth of an inch of the extreme end of each "jaw" is bent inward so that the ends come together; they are then filed to points. This tool is found to be an excellent one to clear away the débris left when a large piece of matrix rock has been shattered by means of the oxyacetylene flame and water.

THE RATE OF SOLUTION OF GYPSUM

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About a mile west of Aspermont, in Stonewall County, Texas, is a scarp formed by two thick layers of white gypsum resting on softer red shales. These rocks belong to the Double Mountain formation of the Permian system. Lying near this scarp are numerous scattered blocks of gypsum which have become detached through erosion.

FIG. 1.—Photo of a gypsum block showing wear by solution

Many of them are furrowed on their upper surfaces by solution grooves, with sharp ridges between, so that there is ample proof that solution by water, rather than abrasion by wind, has played the chief rôle in the erosion of these gypsum scarps.

In November, 1924, Mr. W. C. Thompson and the writer noticed that a large gypsum block, on the south side of the road, was marked with raised letters. Upon closer scrutiny, we found that the words "Wagon Yard" and "Smith" appeared on the upper surface of the

block, while "Feed" and "Water" could be distinguished on the sides. The accompanying photograph shows these words. The watch gives a rough scale.

The words on the sides of the gypsum block had small patches of green paint on them, whereas the letters on the upper surface had lost all but three or four minute traces of similar green paint. These words had evidently been painted on the rock as an advertisement and, in the course of time, rain, beating on the gypsum, had gradually dissolved the rock away except where the paint protected it. Eventually this paint was worn off until it has now nearly gone.

Mr. W. E. Wrather, of Dallas, kindly wrote to a friend of his in Abilene, and through this gentleman, Mr. W. A. Riney, we learned that these words had been painted on the gypsum block by Messrs. Elmer Smith and H. T. Myers in 1917.

This is of interest to geologists as a rough measure of the rate of solution of gypsum. In seven years, through the wearing away of the surface on which the words were painted, these letters acquired an average relief of about $\frac{3}{16}$ inch. They have probably been worn down a little themselves since their original protective coat of paint has almost disappeared. We may say, then, that the gypsum surface has been lowered $\frac{3}{16}$–$\frac{1}{4}$ inch in seven years. This, as shown by the United States Weather Bureau chart for Texas, has occurred where the average annual precipitation—mostly rain—is only 23 inches.

COMPARISON OF THE DEVONIAN ROCKS OF ILLINOIS AND MISSOURI

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ABSTRACT

Certain areas in southwestern Illinois and southeastern Missouri were parts of the same geologic province during Devonian time, and their Devonian history was similar. Likewise, the Devonian history of northern Illinois has much in common with that of central Missouri and Iowa. The Devonian faunas of southern Illinois and southeastern Missouri, however, differ notably from those of central Missouri, northern Illinois, and Iowa. The present paper is a discussion of these various relationships.

The recent publication on "The Devonian of Missouri" by Branson[1] makes this an appropriate time to make a comparison of the succession of Devonian strata in Illinois, Missouri, and Iowa. In both Illinois and Missouri strata are present representing a greater or less part of each of the series of the Lower and Middle Devonian of New York. A few formations are present in Illinois that do not occur in Missouri, the section being a little more complete in the former state than in the latter. The aggregate thickness of the Devonian rocks in Illinois is more than 1,400 feet, while the thickness of the rocks of this system in Missouri does not exceed 1,000 feet.

A comparison of the succession of the formations of the Devonian in Illinois, Missouri, and Iowa is shown in the table given on page 551.

LOWER DEVONIAN

BAILEY LIMESTONE

The Helderbergian series of the Devonian in both Illinois and Missouri is represented by a shaly and cherty limestone formation, known as the "Bailey limestone," which corresponds in age to the New Scotland formation of New York. The thickness of this limestone in Illinois is a little less than that of the corresponding limestone in Missouri, where it reaches nearly 200 feet. The rocks of this formation in the latter state also contain a greater number of

[1] E. B. Branson, *Mo. Bur. Geol. and Mines*, Vol. XVII (2d Series, 1923).

TABLE I

CORRELATION OF THE DEVONIAN ROCKS IN SOUTHWESTERN ILLINOIS, NORTHWESTERN ILLINOIS, SOUTHEASTERN MISSOURI, CENTRAL MISSOURI, AND IOWA

System	Series	Equivalents in the New York Section	Formations in Southwestern Illinois	Formations in Southeastern Missouri	Formations in Central Missouri	Formations in Northwestern Illinois	Formations in Iowa	Vertical Scale in Feet
Mississippian					Grassy Creek shale?	Sweetland Creek shale?	Sweetland Creek shale?	100
DEVONIAN	Upper Devonian		Mountain Glen shale					
					Snyder Creek shale		Lime Creek shale	200
			Alto formation				State Quarry limestone	
					Callaway limestone	Cedar Valley limestone	Cedar Valley limestone	300
					Mineola and Cooper limestones			
						Wapsipinicon limestone	Wapsipinicon limestone	400
	Middle Devonian — Erian	Hamilton	Lingle limestone	Lingle limestone (St. Laurent)				500
			Misenheimer shale	Beauvais sandstone				600
	Ulsterian		Grand Tower limestone	Grand Tower limestone				700
		Onondaga	Dutch Creek sandstone					800
			Clear Creek chert					900
				Clear Creek chert				1,000
	Lower Devonian — Oriskanian	Oriskany	Little Saline limestone	Little Saline limestone				1,100
								1,200
			Grassy Knob chert					1,300
								1,400
	Helderbergian	Becraft						1,500
		New Scotland	Bailey limestone	Bailey limestone				1,600
		Coeymans						1,700
		Keyser						1,800
								1,900

fossils than those in Illinois. However, there is no doubt of the general correspondence of these rocks in the two areas.

GRASSY KNOB CHERT AND LITTLE SALINE LIMESTONE

The rocks of Oriskany age in Illinois consist of a lower chert formation, the Grassy Knob chert, 200 or more feet thick, which grades upward through a transitional zone 12–15 feet thick into a white, coarsely crystalline limestone which also has a thickness of not less than 200 feet. In Missouri the Oriskany strata are represented by a bed of white, coarsely crystalline limestone, called by Dr. Weller the "Little Saline limestone," which corresponds with the limestone formation of the Oriskany in Illinois. Since this limestone in Illinois is clearly the equivalent of the Little Saline limestone of Missouri, this name will be used to designate the limestone formation of Oriskany age in Illinois. The Grassy Knob chert formation, which in Illinois lies below the Little Saline limestone, does not appear to be present in Missouri.

MIDDLE DEVONIAN

ONONDAGA STRATA

The formations in Illinois that correspond in age to some part of the Onondaga of New York are a thick chert formation, the Clear Creek chert, 300 or more feet thick, which passes upward into a sandstone, the Dutch Creek sandstone, about 35 feet thick, which in turn grades upward into a limestone, Grand Tower limestone, having a thickness of nearly 125 feet. With the possible exception of the Dutch Creek sandstone, the above-mentioned formations of the Onondaga are also present in southeastern Missouri. The Clear Creek chert is exposed in Perry County, across the river from Grand Tower, and the Grand Tower limestone is strongly developed in Ste. Genevieve County where Dr. Weller has found it conformably overlying the Little Saline limestone, and attaining a thickness of about 250 feet. The Dutch Creek sandstone has not been reported from Missouri, but as it occurs at the top of the Clear Creek chert just across the river in Illinois, it will probably be found in some of the localities where the Clear Creek chert is exposed in Perry County, Missouri.

HAMILTON FORMATION

The strata of Hamilton age in Illinois have been called the "Lingle limestone," and have a thickness of about 100 feet. In a few places a shale bed is present beneath the Lingle limestone. This shale corresponds in its position and fauna with the Marcellus shale of the New York column. In Ste. Genevieve County, Missouri, rocks of the same general age as the Hamilton of New York, and the Lingle limestone of Illinois, are well developed along St. Laurent Creek, in northern Perry County, and along Little Saline Creek, Ste. Genevieve County, Missouri, where they overlie a sandstone, and have a thickness of about 275 feet.

UPPER DEVONIAN

ALTO FORMATION

In southwestern Illinois there occur siliceous, shaly limestones, 90–100 feet thick, which were deposited in a sea that was connected with the New York province during upper Devonian time, but corresponding rocks have not been reported in Missouri.

DEVONIAN OF THE ARCTIC OR NORTHWEST PROVINCE

The Devonian rocks in Illinois and Missouri that belong to the Arctic or Northwest province are found north of the latitude of St. Louis, while the Devonian rocks of southwestern Illinois and southeastern Missouri, described above, were deposited in seas that advanced from the south and east, and do not occur in western Illinois and eastern Missouri as far north as St. Louis. These rocks belonging to the Northwest province are better developed in Iowa than in either Illinois or Missouri. Those in Illinois were deposited in an extension eastward of the sea that covered the greater part of eastern Iowa, and the corresponding rocks in Missouri accumulated in a southward extension of that sea.

In Iowa the Devonian rocks consist of the Wapsipinicon limestone at the base, above which is the Cedar Valley limestone, and still higher strata comprise the State Quarry and Lime Creek formations. Rocks corresponding to the Wapsipinicon and Cedar Valley limestones are also present in northwest Illinois, and the names used in Iowa are applied to these formations in Illinois.

In 1920 the writer discussed "The Devonian Formations in Illinois,"[1] and referred all of these rocks of Devonian age in Iowa and northwest Illinois to the Upper Devonian. In a paper published the following year Thomas[2] also assigned all of the Devonian rocks of Iowa to the Upper Devonian.

The Devonian rocks in central Missouri belong to the same province as those in Iowa and northwest Illinois, and are thought by the writer to be also of Upper Devonian age. They have been assigned by Branson to the following formations:[3] Cooper limestone, Mineola limestone, Callaway limestone, and Snyder Creek shale.

COOPER LIMESTONE OF MISSOURI

Professor Branson says of the Cooper limestone:

> It is a bluish gray, compact, very fine grained rock that resembles the so-called lithographic limestone of northeastern Missouri. The thickness ranges up to 30 feet . . . . but the average is less than 15 feet. . . . . The original extent of the Cooper is problematical. It did not reach far east of Boone County, as in that direction the Mineola limestone occupies the same horizon. . . . . The Cooper seas may have connected northward with the earliest middle Devonian seas of Iowa. The following list contains all of the identifiable forms that the writer has collected from the Cooper limestone:
>
> *Favosites alpenensis* Winchell
> *Streptelasma cooperensis* Branson
> *Atrypa reticularis* (Linnaeus)
> *Gypidula marionensis* Greger
> *Lunulicardium grande* Miller and Gurley
> *Turbinopsis (Pleurotomaria) providencis* Broadhead[4]

Dr. Branson says "the Cooper faunas are meager and not diagnostic," and yet he correlates this limestone with the Onondaga of New York, of which the Grand Tower limestone of Illinois and Missouri is the equivalent. Not a single one of the species of fossils listed above occurs in the Grand Tower limestone, except *Atrypa reticularis*, which has no value as a marker on account of its long vertical range. *Favosites alpenensis* is more characteristic of the Wapsipini-

[1] T. E. Savage, *Amer. Jour. of Sci.*, Vol. XLIX (March, 1920), pp. 179–82.

[2] A. O. Thomas, "Echinoderms of the Iowa Devonian," *Iowa Geol. Survey*, Vol. XXIX (*Ann. Rept.*, 1919 and 1920), pp. 385–552. 1921.

[3] E. B. Branson, *op. cit.*, p. 2.

[4] *Ibid.*, p. 12.

con and especially the Cedar Valley formation of Iowa and northwest Illinois than of any other horizon. The figures given by Branson of *Gypidula marionensis* resemble young shells of *Gypidula comis* which is common in Upper Wapsipinicon rocks. The other species in the list are known only from central Missouri. Of these, *Streptelasma cooperensis* occurs also in the Callaway limestone, which corresponds with some part of the Cedar Valley limestone. To the writer the fossils indicate very late Wapsipinicon or early Cedar Valley age for the Cooper limestone more definitely than that of any other horizon. They certainly show no indication of Onondaga age for the Cooper limestone.

MINEOLA LIMESTONE

Dr. Branson says:

> One of the typical phases of the Mineola is a highly crystalline, crinoidal limestone, almost white in color, which weathers readily into a crumbly condition. . . . . Another phase is a yellowish to pinkish, gray limestone, which contains a large number of small, irregular cavities produced by the solution of fossils. In most places the limestone is sandy. . . . . The disconformity between the Mineola and the Callaway, and the final determination of unconformity, rests on the thickening and the thinning of the Mineola and the overlap of the Callaway. . . . . The greatest thickness examined is about 50 feet. . . . . Conditions under which the Mineola and Cooper limestones were deposited seem to have been almost identical and the barrier between the two seas must have been a low divide between wide shallow bays.

The following is a list of all of the previously identified Mineola fossils given by Dr. Branson. The new species he lists would be of no help in determining the age and correlation of the strata. A star in front of the name in the list indicates that the writer has collected the species from the Devonian, mostly Cedar Valley limestone, of Iowa. An interrogation point in front of the name indicates that in the writer's judgment the species would be better compared with a species of the genus occurring in the Cedar Valley limestone of Iowa and northwest Illinois than referred to the name in the list.

LIST OF PREVIOUSLY DESCRIBED FOSSILS FROM THE MINEOLA LIMESTONE

* *Aceruularia davidsoni* (Ed. and H.)
* *Favosites alpenensis* (Winchell)

? *Nucleocrinus verneuili* (Troost)
* *Cyclotrypa communis* (Ulrich)
* *Athyris vittata* (Hall)
* *Atrypa reticularis* (Linnaeus)
* *Cranaena romingeri* (Hall)
* *Cyrtina hamiltonensis* (Hall)
* *Eunella lincklaeni* (Hall)
* *Pentamerella arata* (Conrad)
* *Pholidostrophia iowensis* (Owen)
? *Productella spinulicosta* (Hall)
* *Reticularia fimbriata* (Conrad)
? *Schizophoria of. propinqua* (Hall)
? *Schuchertella cf. pandora* (Billings)
* *Spirifer euryteines* (Owen)
* *Spirifer subvaricosus* (Hall and Whitfield)
? *Spirifer varicosus* (Hall)
* *Stropheodonta demissa* (Conrad)
? *Stropheodonta inaequiradiata* (Hall)
? *Conocardium ohioense* (Meek)
Euryzone lucina (Hall)
Platyceras of calantica (Hall)
* *Platyceras carinatum* (Hall)
* *Platyceras conicum* (Hall)
* *Platyceras cf nodosum* (Conrad)
? *Proetus crassimarginatus* (Hall)
* *Dinichthys pustulosus* (Eastman)
* *Ptyctodus calceolus* (Newberry and Worthen)

The species of fossils listed above are practically those of the Iowa Devonian fauna. If Dr. Branson had been familiar with the fossils of the Devonian of Iowa it is certain he would never have stated that "the fossil content and relationships of the Mineola indicate its correlation with the Onondaga of Illinois, Indiana and eastward."[1] He says: "Remains of *Eunella lincklaeni*, *Pentamerella arata*, and *Athyris vittata* constitute the larger part of the fossils in central Missouri." It is significant that all of these species are common in the Cedar Valley limestone of Iowa, and not one of them can be considered in any sense diagnostic of the Onondaga in Illinois or elsewhere. He states that "in Northeastern Missouri, Ralls County, the fauna is more varied. *Spirifer subvaricosus*, *Cranaena romingeri*,

[1] E. B. Branson, *op. cit.*, pp. 22 and 23.

three species of *Stereocrinus*, *Acervularia davidsoni*, *Favosites alpenensis*, and *Ptyctodus calceolus* are common forms." Every one of these species is also common in the Cedar Valley limestone of Iowa. He says that in the crinoidal member various species of *Megistocrinus* and *Stereocrinus* are abundant, but nearly all of the heads are exfoliated and specific identification is impossible. He describes three new species of each of these genera. It is significant that these same crinoid genera are represented in Iowa by several species, Thomas[1] having recently figured and described seven species of *Megistocrinus* and two species of *Stereocrinus* from the late Wapsipinicon and Cedar Valley limestones of that state. Several species of *Platyceras*-like shells occur in the Mineola limestone, but judging from Branson's figures of these, they have a much closer resemblance to species found in the lower Cedar Valley and upper Wapsipinicon limestone, near Solon, in Johnson County, Iowa, than to the species of *Platyceras* that occur in the Onondaga or Grand Tower limestone in Illinois. Branson suggests:

> the presence of such species as *Spirifer varicosus*, *Productella spinulicosta*, *Schizophoria propinqua*, and *Stropheodonta inaequiradiata* indicates Onondaga rather than later time but these species are rare and some of the identifications are uncertain.

The figures he gives of these shells indicate that they were poorly preserved. The figures of *Spirifer varicosus* and *Stropheodonta inaequiradiata* appear to the writer to be such as to make uncertain their identification. The shells of *Productella spinulicosta* and *Schizophoria propinqua* should be compared with those identified from the Iowa Devonian under the names *Productella subalata* and *Schizophoria iowensis*, respectively. *Conocardium ohioense* resembles a species the writer has collected from the Cedar Valley limestone and identified as *Conocardium cuneus* var. *americanum* Keyes. The figures of *Proetus crassimarginatus* indicate that the specimens were too fragmentary for certain identification. The same form is also listed from the Snyder Creek shale. Branson's figure of *Nucleocrinus verneuili* appears to the writer more closely similar to one of the species of *Nucleocrinus* figured by Thomas from the Devonian limestone of Iowa than it does to the species *Nucleocrinus verneuili*. The

[1] A. O. Thomas, *op. cit.*, pp. 442–58.

fauna of the Mineola limestone impresses the writer as distinctly that of the Cedar Valley limestone of Iowa and northwest Illinois. This limestone is then correlated with the Cedar Valley limestone of Iowa, and referred to the Upper Devonian, as shown in the correlation table on page 551.

CALLAWAY LIMESTONE

The Callaway limestone of Missouri is similar in general character and fossil content to the Cedar Valley limestone of Iowa and northwest Illinois, and there is no doubt that it is equivalent in time to the middle and upper parts of this formation of the Iowa Devonian.

SNYDER CREEK SHALE

Branson has shown that the Snyder Creek shale of Missouri and the Lime Creek shale of Iowa have twelve species of fossils in common, although only four of these—*Stromatopora solidula* Hall and Whitfield, *Chonophyllium ellipticum* Hall and Whitfield, *Cranaena calvini* (Hall and Whitfield), and *Pugnoides altus* (Calvin)—have much diagnostic value. It seems possible, as Branson suggests, that the Lime Creek sea and Snyder Creek sea were parts of the same province, and were probably more or less contemporaneous, but the connection between these seas was not direct or continuous during the greater part of the time of deposition of these sediments, so that the faunas did not mingle to a great extent, and consequently developed a considerable amount of divergence. However, the presence of such species as *Athyris fultonensis*, *Spirifer asper*, and *Spirifer euryteines* in the Snyder Creek fauna would indicate a somewhat closer relation of this formation with the Cedar Valley limestone than is shown in the species of the Lime Creek fauna of Iowa.

The Sweetland Creek shale of Iowa and northern Illinois is doubtless of about the same age as the Grassy Creek shale of central Missouri, but both of these formations are considered by most geologists to be of early Mississippian age. The Mountain Glen shale of southern Illinois does not seem to be represented in Missouri.

REVIEWS

La Detérmination des Plagioclases dans les Coupes Minces. By L. DUPARC AND M. REINHARD. Mem. Société de physique et d'histoire naturelle de Genève, Vol. XL, fasc. 1, 1924. Quarto, pp. 149, pls. 13, figs. 69.

The senior author of this important monograph received his early training in petrography under Michel Lévy and Fouqué, and later became acquainted at first hand with the work of the great Russian mineralogist, Federoff. He is, therefore, peculiarly well qualified to prepare a comprehensive treatise on the subject. Federoff discovered some years ago that feldspars exhibit several types of twinning in thin sections which are unknown in larger crystals and therefore undescribed in the literature; he was enabled to recognize and describe these types of twinning as a result of studying feldspars with his "universal stage" methods.

The authors of the new monograph on the plagioclases start with the most accurate data on the crystallography and optic properties of carefully analyzed plagioclases contributed by Becke, Grosspietsch, Kratzert, and Wülfing, and deduce by graphic methods the properties of all other plagioclases, not only with respect to the usual types of twinning, but also with respect to the newly discovered types of twinning. These are presented in the numerous figures and plates which greatly increase the usefulness of the work.

This monograph not only gives more accurate and far more complete optic data for the determination of the plagioclase feldspars by the usual methods than have been assembled heretofore, but also gives diagrams, directions, and illustrations for the use of the methods of Federoff as applied to the feldspars. The authors show that these methods of Federoff are the only ones which give complete and certain results, not only as to the composition of the plagioclase, but also as to the type of twinning which is present.

This discussion of feldspars is confined to soda-lime types; it is to be regretted that data are not yet available to show accurately the effects of $KAlSi_3O_8$ (and other possible isomorphous molecules) upon the properties of the pure soda-lime plagioclases.

A. N. WINCHELL

The Collection of Fossils and Rocks from Somaliland, By B. N. K. WYLLIE and W. R. SMELLIE. Monograph of the Geological Department of the Hunterian Museum, Glasgow University, 1925. Pp. 180. pls. 18, figs. 26.

This monograph is of particular interest in that it confirms the view that the basin of the Gulf of Aden was formed by fault-bounded subsidences at dates which agree with those previously suggested for the Great Rift Valley. Somaliland has the normal East African sequence, consisting of a foundation of pre-Paleozoic crystallines which remained above sea-level throughout the Paleozoic; Triassic terrestrial beds in which there are some volcanic rocks; Jurassic, Cretaceous, Eocene, and Oligocene sediments; and Pleistocene or Upper Pliocene basalts and coral formations. The first sea invasion took the form of a Jurassic gulf. In the Cretaceous this gulf was replaced by land; later it was covered in part by an Eocene sea. Renewed uplift occurred in the Upper Eocene and Lower Oligocene, and during this interval a series of faults, which are continuations of the boundary faults of the Red Sea, broke across Somaliland. Upper Oligocene submergence followed, and, during Upper Pliocene times, basalt eruptions occurred which were connected with renewed down-faulting in the Gulf of Aden.

The rich Somaliland fauna is also described and illustrated in the report.

L. F. A.

Evolução da Estructura da Terra e Geologia do Brasil. By ALBERTO B. P. Leme. Rio de Janeiro: Imprensa Nacional, 1924. Pp. 368, figs. 14. Colored geologic map.

The chief interest of this volume lies not in Part I, which is an introductory exposition of geologic principles, but in Part II, the geology of Brazil. Here the reader may obtain in concise form the leading facts of Brazilian geology as understood at the present time. The treatment is simple and direct. A colored geologic map of the entire country, necessarily somewhat generalized, is a useful accompaniment of the text.

R. T. C.

A Chart Showing the Chemical Relationships in the Mineral Kingdom. By P. C. PUTNAM. New York: John Wiley & Sons, 1925. $3.00.

1611 minerals are listed by means of reference numbers in a 3 by $1\frac{1}{2}$-foot chart accompanied by a 31-page booklet of explanation. The chart

shows in semigraphical fashion the possible combinations of elements as they occur in nature, as well as all the minerals containing a given element or combination of elements.

D. J. F.

The Volcanic Activity and Hot Springs of Lassen Peak. By A. L. DAY and E. T. ALLEN. Carnegie Institution of Washington. Pub. No. 360, 1925. Pp. 186, pls. 13, figs. 81.

The first part of this paper deals with the volcanic activity of Mount Lassen itself, especially a description of the explosive outbursts of 1914 and 1915. After a clear presentation of the field data, the authors give the results of a laboratory investigation of the chemical and physical aspects of the problem. Among the conclusions to be noted are: (1) the low temperature of the eruption (less than 800° C.); (2) the prominent part played by steam in the eruptions; and (3) the absence of chemically active gases. In the discussion of causes the following relations are brought out: (1) much water pouring into the crater in May, 1914; (2) heavy accumulation of winter snow preceding the culminating outburst in May, 1915; (3) warm rocks and little snow accumulation in the winter of 1915–16; (4) accumulation of snow again in the winter of 1916–17 and the period of spring melting in May, 1917, marked by violent explosions.

Part II deals with the hot springs near the volcano. A description of the springs is given, and the results of an extensive laboratory study. It is interesting to note that kaolin, i.e., clay, is formed from feldspar by acid waters; sericite, by alkaline waters; and that temperature does not determine whether kaolin or sericite will form, but only which variety of kaolin (kaolinite, halloysite, or leverrierite) forms. Sulphuric acid is formed by the oxidation of hydrogen sulphide first to free sulphur and then to the acid.

The conclusion is reached that the water of the springs is mainly surface water, varying in amount with the seasons. A certain portion of the water, however, is derived from the underlying magma. Arising in the form of steam along with other volcanic gases through clefts in the rock, it is condensed by the ground waters and becomes mingled with them.

Some of the heat, perhaps the larger part of it, is derived from the magmatic steam. Another portion is conveyed through the lower depths of rock by conduction, ultimately vaporizing some of the ground water which then participates in the convection of heat.

The volume is beautifully illustrated and is an important contribution to vulcanology and to our knowledge of hot springs.

J. H. HUGHES

The Geology and Mineral Resources of Wise County and the Coal-bearing Portion of Scott County, Virginia. By J. BRIAN EBY, with chapters by M. R. CAMPBELL AND G. W. STOSE. Virginia Geological Survey, Bull. 24, 1923. Charlottesville, Va. Pp. 617, figs. 55, pls. 45.

The items of particular interest in this publication are the stratigraphy, the coals, and the Clinton iron ores. Twenty formations, occurring between the base of the Ordovician and the top of the Pennsylvanian, are described in detail. These give an excellent notion of the Paleozoic stratigraphy of the Appalachian Plateau. Four hundred and four pages are devoted to the description of the coal of this area, which is the most important in Virginia. In discussing the Clinton iron ores the author points out that the diversity of opinion regarding their origin arises from attempts to apply one theory to all occurrences. The evidence in Wise County points to original deposition with minor addition of iron oxides by circulating iron-bearing waters.

L. F. A.

Special Reports on the Mineral Resources of Great Britain, Volume VIII. *Iron Ores—Hematites of West Cumberland, Lancashire and the Lake District.* By BERNARD SMITH. Second Edition. Pp. 236, pls. 5, figs. 31. London: H. M. Stationery Office, Adastral House, 1924. 5*s*.

In this memoir of the Geological Survey an account is given of the hematite mines in the West Cumberland and Furness districts. Detailed accounts of the mines are preceded by a general description of the geology of the iron fields, the variety, constitution, analyses, and statistics of output of the ores, and their probable origin. The ore occurs chiefly in the Carboniferous limestone and the older rocks of the Central Lake district.

R. T. C.

Travaux du Service Géologique de Pologne. Warsaw: J. Mianowskiego, 12 Rue Nowy Swiat 72.

A series of bulletins and other publications, inaugurated in 1921, containing many important papers upon a portion of Central Europe which is comparatively unfamiliar to most American geologists. The tectonics of the Carpathians form the basis of several papers of much general interest. While published in Polish, nearly every article has an adequate résumé in French.

R. T. C.